PROJECT *Skyfire*

A PROGRESS REPORT ON LIGHTNING FIRE AND ATMOSPHERIC RESEARCH

by

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SUMMARY

This report describes the factors which led to the establishment of Project Skyfire and presents the first results of its operation. Skyfire is a program designed to acquire basic scientific information about lightning fires in western forests, the atmospheric and cloud conditions which produce them, the nature of the local weather before, during, and after their occurrence, and the possibility of modifying lightning storms by cloud seeding.

The Skyfire cloud survey is based on an integrated network of mountain-summit stations. During the summer of 1953 twenty-five of these stations were manned by forest-fire observers who were given special training in cloud identification during a 3-day period of intensive instruction just prior to reaching their lookout stations.

The area covered by these special observations consists of about 20 million acres of forested mountains in eastern Washington, northern Idaho, western Montana, and northwestern Wyoming. In this region more than 70 percent of the forest fires are caused by lightning.

In making the daily cloud surveys a simple coding system was used to report the geographic location of small cumulus clouds and their subsequent life cycle. Data were also obtained on middle and high clouds in order to study the relationship of certain distinctive cloud forms and characteristics to fire weather and the presence or absence of a jet stream in the vicinity.

At key mountain locations special time-lapse movie cameras were installed to obtain typical cloud records. A special sphere camera photographed the day-by-day life cycle of clouds in suspected cloud-breeding areas.

The results of the first season's operation were very satisfactory. Preliminary results imply a good correlation between certain fast-moving altocumulus and cirrus clouds and the presence of the major axis of a jet stream. Some of the most serious of the lightning fire outbreaks showed a close relationship to the presence of a jet stream over the area. More than 2000 feet of time-lapse cloud movies were obtained. Some of these indicate the importance of the southwestern area of the region as a primary source of the fast-moving type of thunderstorm which sweeps over the observation area.

Based on the findings of the 1953 season a group of 17 stations in the northern Rockies and Oregon operated in 1954. In the middle of the 1954 fire season 8 cloud survey stations were added in California. Special attention was given to suspected cloud-breeding areas. Improved methods of reporting cloud observations have been devised and a new cloud manual made available. Special reports were transmitted over a radio network to permit the plotting of daily cloud maps. Special weather analyses were prepared on a daily schedule. The Munitalp-University of Washington-Forest Service mobile weather observatory was employed in the field for special observations.

Figure 1. Typical lightning-caused fires in northern Rocky Mountain forests.

I. THE LIGHTNING FIRE PROBLEM

Project Skyfire is basic research of the atmosphere and its relation to lightning fires in western forests. The long-range objectives of Project Skyfire are to gain a better understanding of the atmospheric factors influencing the occurrence, behavior, and control of lightning fires and to determine the feasibility of preventing or reducing lightning fires through cloud-modification operations.

LIGHTNING FIRE CHARACTERISTICS

Lightning fires are a multimillion-dollar problem in western forests (figures 2 and 3). During the 23-year period 1931-1953 over 134,000 lightning-caused forest fires occurred in the western United States. Nearly 2,000,000 acres were burned by these fires. In the Rocky Mountain States 65 percent of the forest fires are lightning caused (1).

The number of lightning fires varies widely from year to year (figure 4). The great variations in lightning-fire occurrence are due both to the individual characteristics of lightning storms and to the dryness of fuels in the storm areas. Some lightning storms are accompanied by a considerable amount of rain which reduces the number of fires started, but a more common pattern in western forests and especially in the Rockies is for very little rain to occur with the summer storms. Sometimes relatively mild storms can produce disastrous fire situations if pre- and post-storm weather is dry and windy. In the national forests of western Montana and northern Idaho over 300 lightning fires have started in a 24-hour period (2). In the same area daily loads of 50 or more lightning fires occur in every month from May through September and in July, 1940, nearly 1500 fires occurred in a 10-day period (figure 5).

Zones of lightning-fire occurrence have been determined from studies of thousands of fires (1). These studies have shown the ignition rate of lightning fires by time of day and elevation zone in the northern Rockies (figures 6 and 7). As a result of this research the general trouble spots are known and it is now possible to proceed with the next step of finding and recording the action of the cloud-breeding spots for these areas.

One of the major factors in lightning fires is their behavior in the initial stages following ignition (3). The meteorological factors associated with lightning may either favor, or retard the initial rate of spread of fires. Moisture accompanying some storms retards ignition and initial rate of spread. In some cases moisture makes the fire-detection job difficult because of the tendency for the fires to smolder and show little smoke. Later when dry weather comes, these fires may appear unexpectedly several days after the lightning storm which started them. Severe downdraft winds are frequently associated with lightning storms. These winds may fan freshly started fires, blow sparks from strikes in snags and treetops, and scatter burning embers to surrounding fuels.

Figure 2. In critically dry weather, lightning fires like this one may spread rapidly over large forest areas.

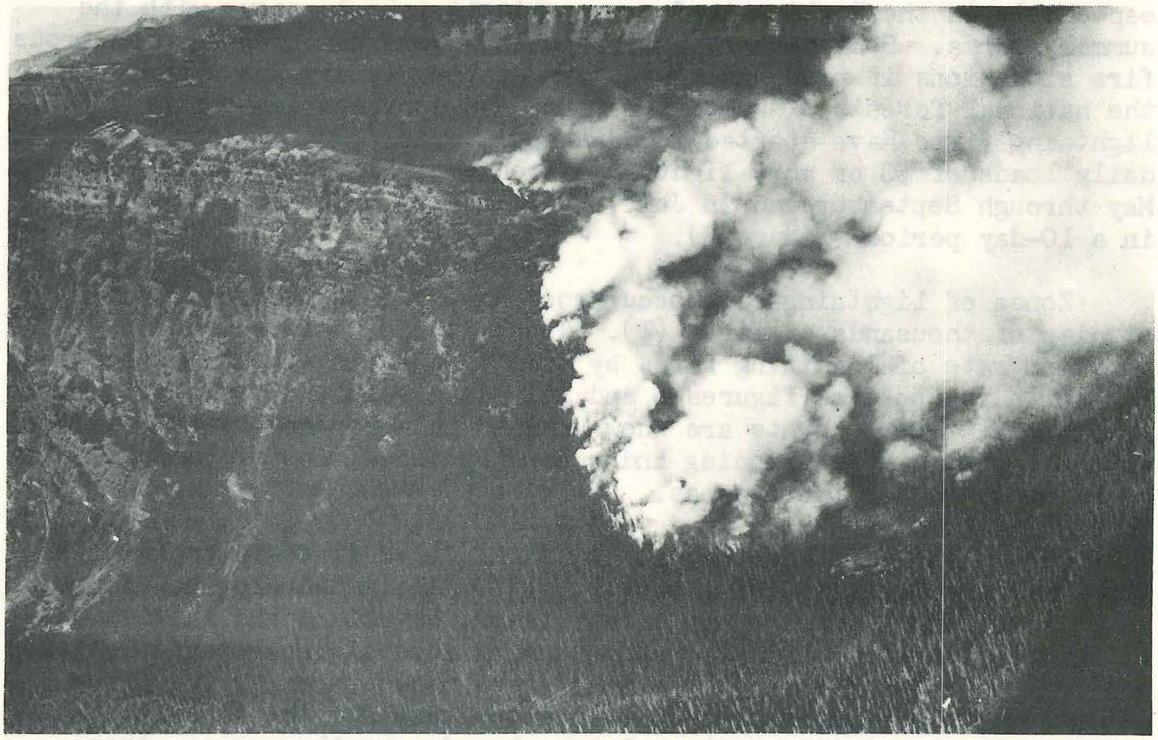


Figure 3. Lightning fires often start near ridgetops in rough, mountainous country where control operations are difficult and expensive.

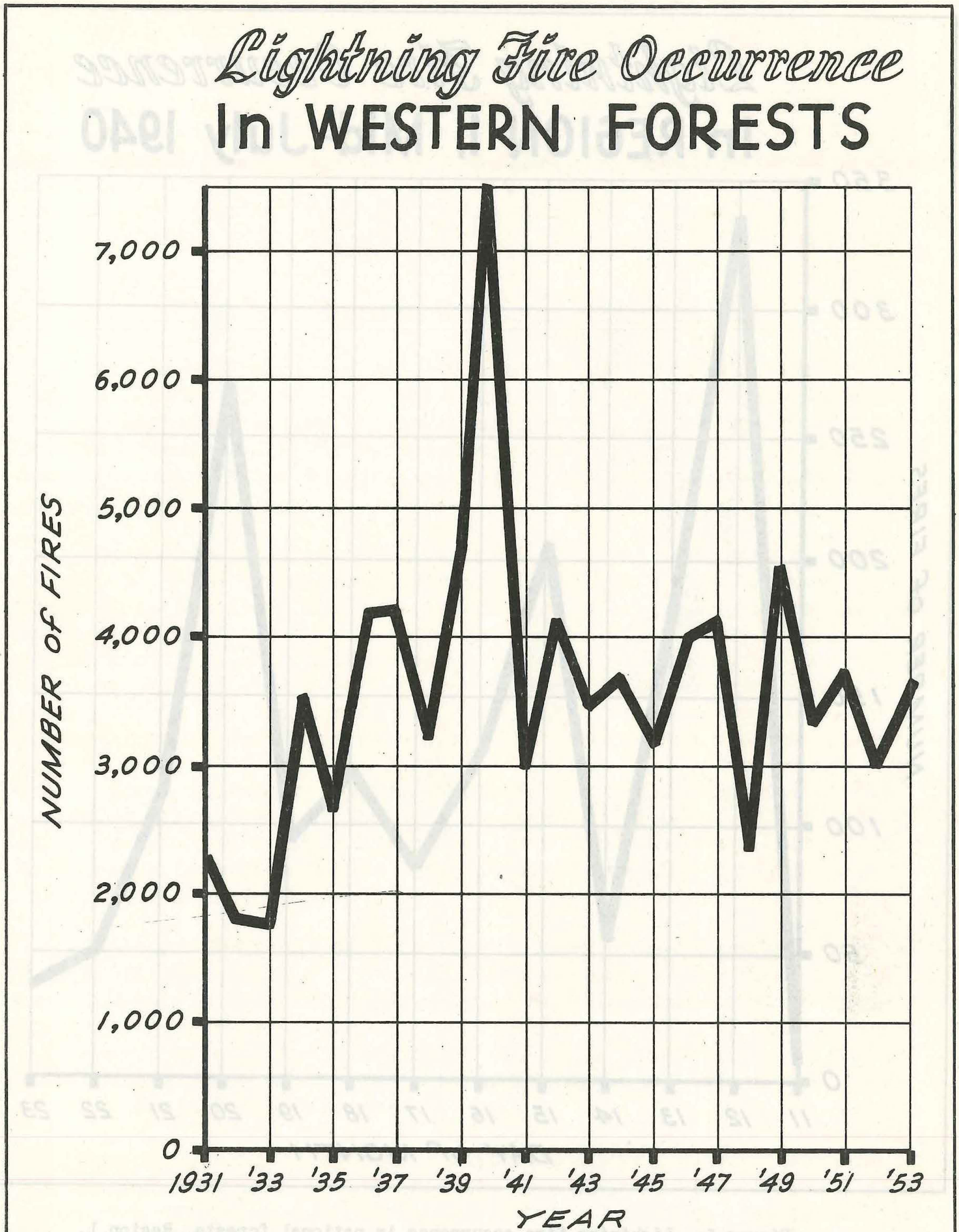


Figure 4. Lightning fire occurrence on lands protected by Federal, state, and private agencies in the 12 western states, 1931-1953. (Basis 134,534 fires reported to U. S. Forest Service in states of Montana, Idaho, Wyoming, South Dakota, Colorado, New Mexico, Arizona, Utah, Nevada, Oregon, Washington, and California.)

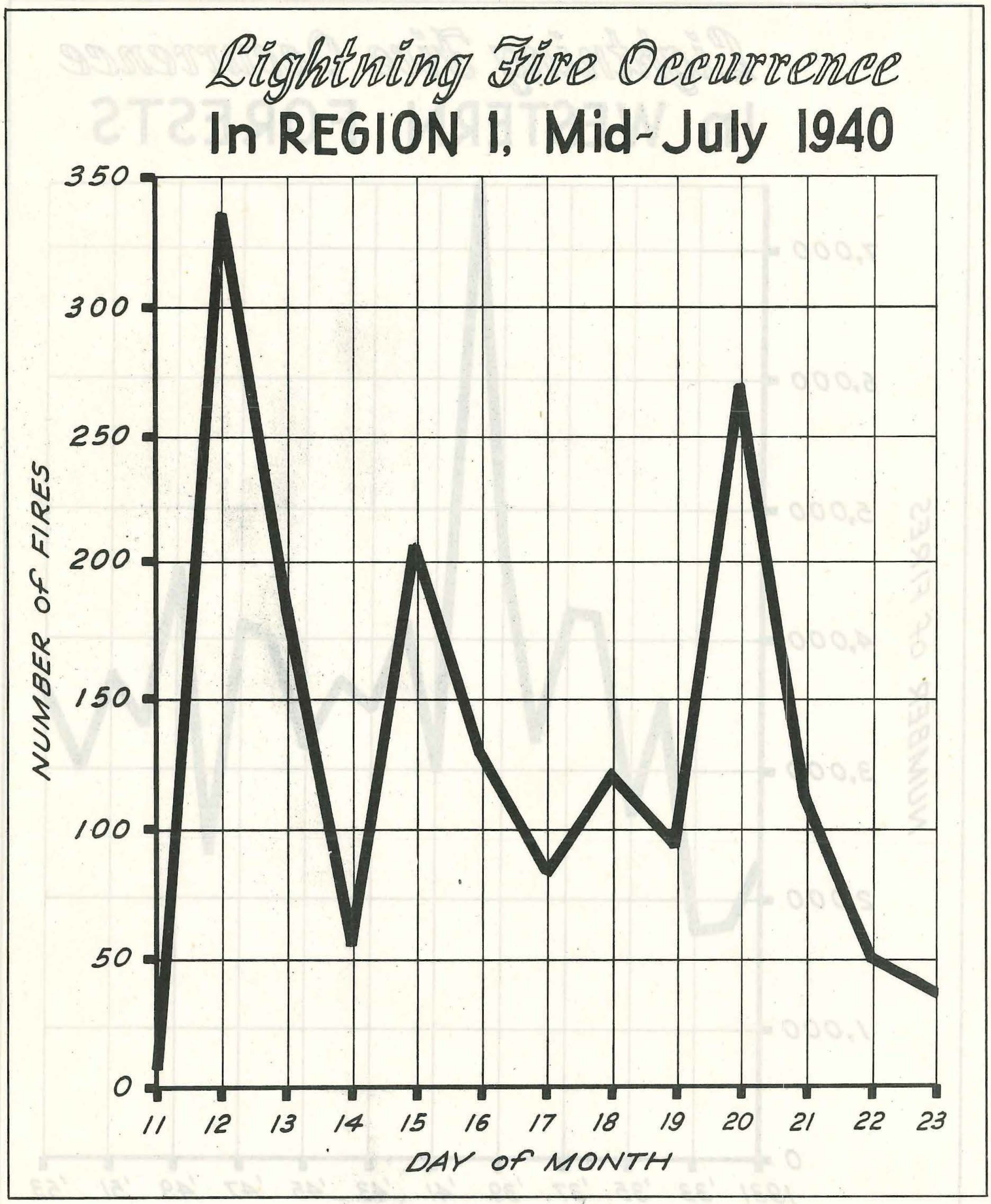


Figure 5. Lightning fire occurrence in national forests, Region 1, mid-July 1940.

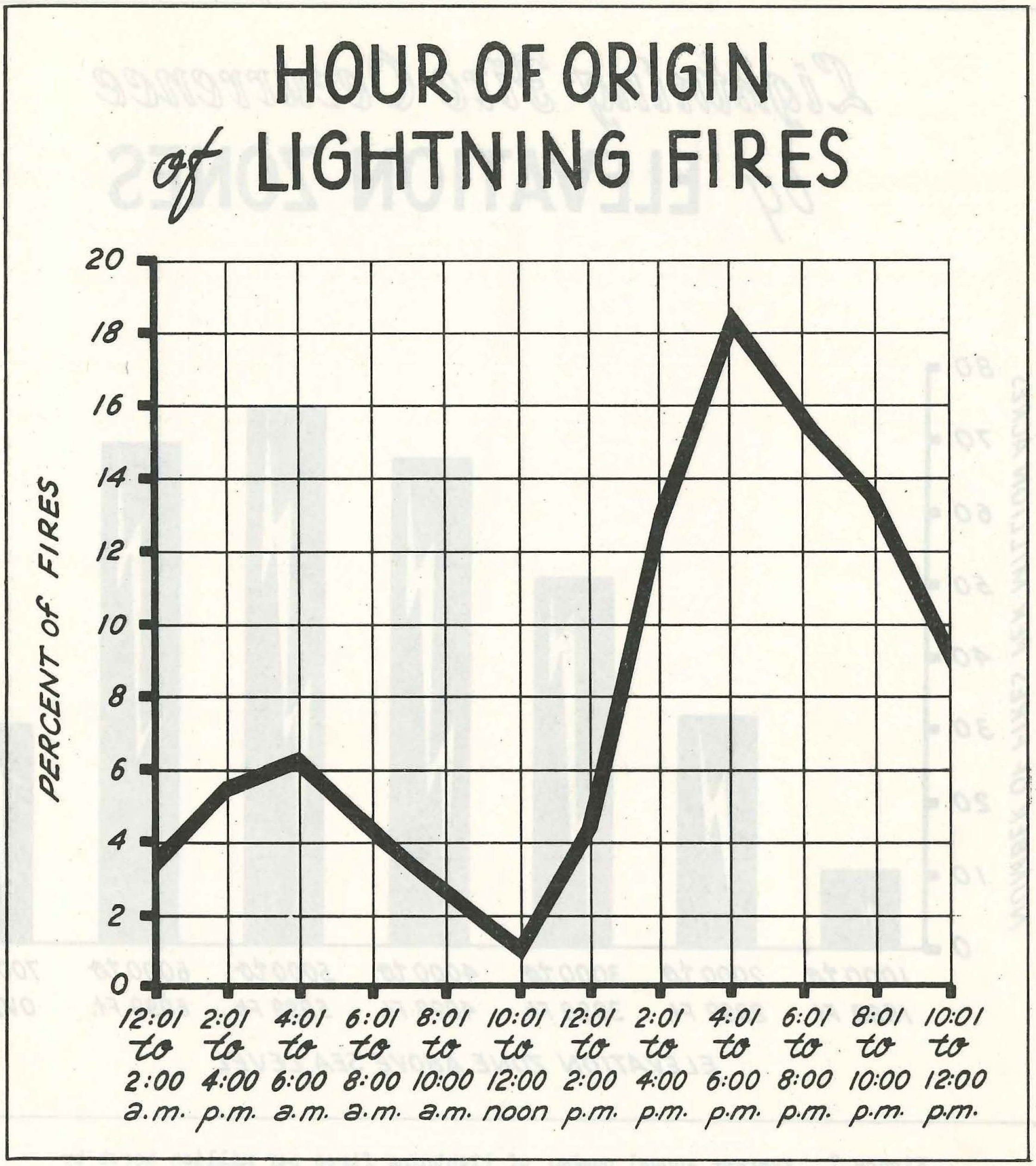


Figure 6. Percent of lightning fires starting in each 2-hour period, national forests west of Continental Divide, Region 1.

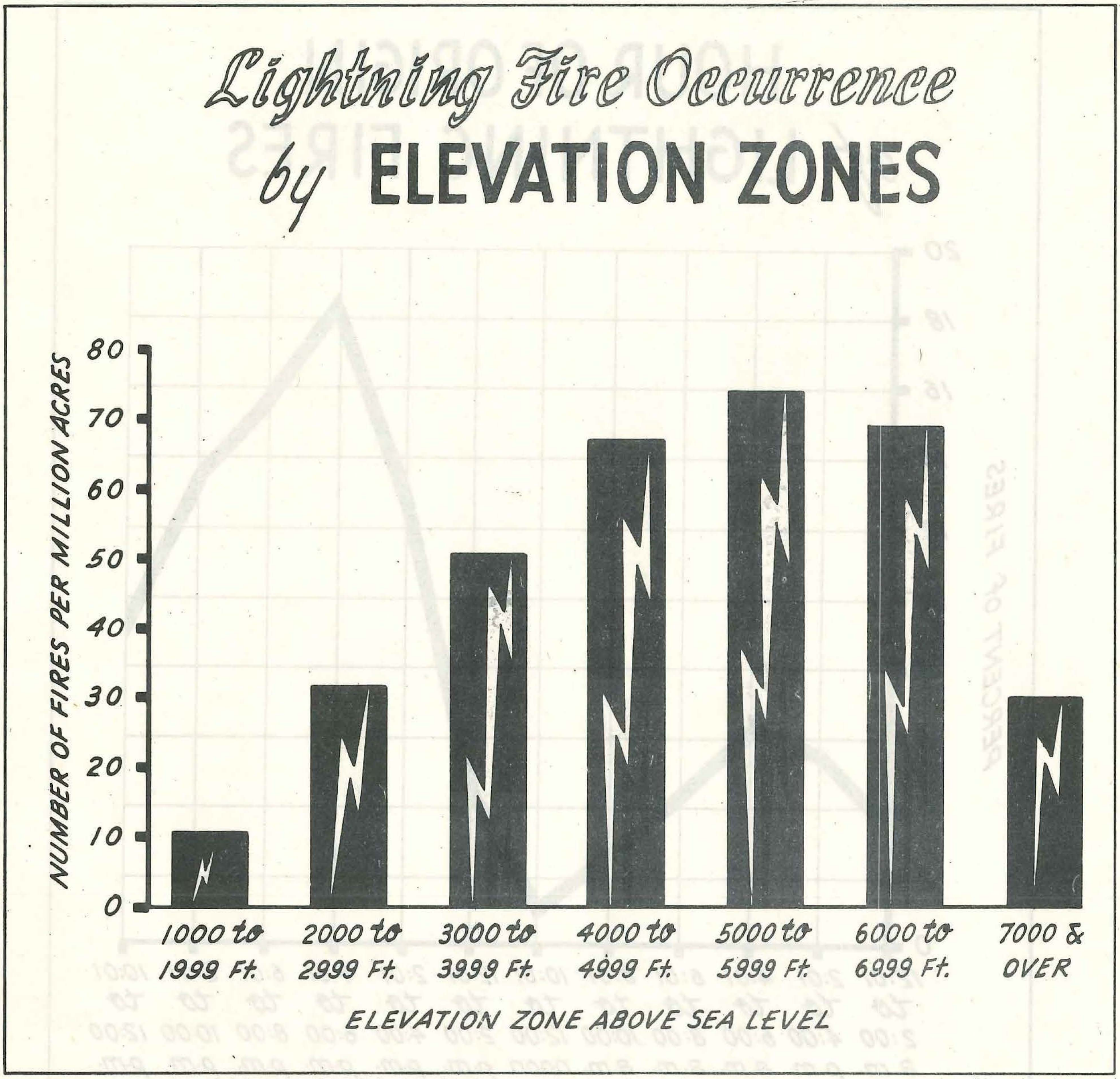


Figure 7. Average annual number of lightning fires per million acres by elevation zone above sea level, national forests west of Continental Divide, Region 1.

THE LIFE CYCLE OF LIGHTNING FIRES

The concern of forest-fire-control organizations in lightning fires begins with the prediction that a storm may occur and continues through the various stages of cloud development, lightning action, precipitation, storm dissipation, and post-storm weather. Documentation of the complete life cycle of lightning fires including pre- and post-storm weather and the details of the storm itself is of great importance in the development of a better understanding of fire-control requirements. The development of such life-cycle information is one of the prime objectives of Project Skyfire.

The meteorological factors associated with lightning are complex and not fully understood. Continued research is necessary to probe the remaining unknowns of lightning phenomena. Project Skyfire hopes to provide some of this information and especially that related to cloud formation over the western mountains. Questions to receive attention include: When and where do cumulus clouds form? What are the most important cloud-breeding areas? What are the major lightning-storm paths? What are the relationships of middle and high clouds to the jet stream, and the jet stream to lightning-fire occurrence and behavior?

THE RESEARCH OPPORTUNITY

Progress in meteorology and forestry point to the opportunities for developing better methods for the control--and possibly for the prevention--of lightning fires. More knowledge is being gained of the atmosphere--of clouds and their action, of high-altitude winds, of regional climatic patterns, and of the dynamics of weather. Experience in forest-fire-control operations has indicated the general characteristics of lightning fires. Recent forest-fire research has provided general information on when and where lightning fires occur and on their severity according to fuel, topography, and surface weather conditions (1).

The experiments of Project Cirrus (10, 12), and of numerous industrial and commercial meteorologists have demonstrated that convective clouds may be altered through cloud-seeding operations. Research workers in many countries of the world are performing theoretical and experimental research on cloud physics. In the United States there are now many research and commercial cloud-modification programs underway. Research has been started on hail prevention through cloud-modification processes; this may be closely related to lightning reduction. Some efforts are being made to prevent lightning storms by both ground and aerial seeding operations.

Forest-fire-control organizations in the western United States are uniquely equipped to assist in atmospheric research. Personnel at mountain-top forest-fire lookout stations are in a commanding position to make regular observations of clouds and lightning storms. Likewise the pilots, fire observers, and smokejumpers of the aerial fire-control

forces can assist in obtaining information needed in atmospheric and lightning fire research. Throughout the western United States a network of fire-weather stations provides data related to lightning fire occurrence and behavior. The radio communications systems of fire-control organizations enable rapid transmission of lightning, cloud, and general fire-weather reports for daily analysis by research personnel.

The over-all impact of these developments in meteorology and forestry is the creation of a favorable situation for atmospheric and lightning fire research. The need for such research is great and the opportunities for progress are equally great.

THE EARLY RESEARCH EFFORTS

In 1947 Mr. Harry Gisborne, then Chief of Fire Research at the Northern Rocky Mountain Forest and Range Experiment Station of the U. S. Forest Service, visited Dr. Vincent J. Schaefer, then a Research Associate at the General Electric Research Laboratory, Schenectady, New York, for a discussion of thunderstorms and the possibilities of preventing their formation. Schaefer told Gisborne that, based upon current knowledge and the new discoveries likely to follow the intensive research effort then getting underway, there was a good chance that one could hope eventually to exercise some degree of control over damaging storms. He pointed out the need for acquiring field data by direct observation and was invited to initiate such a program in the northern Rocky Mountains.

In July and early August of 1948 Schaefer, Gisborne, and Barrows observed, photographed, and measured a number of thunderstorms which occurred in the Selkirk Mountains of northern Idaho. In a report prepared at the end of the season a number of recommendations were made (15). These pointed up the distinct possibility that the local storms might be modified by proper seeding methods but emphasized the importance of gathering much more field data by mountain-top observations.

Some of these recommendations were carried out during 1949 but the observational and research program suffered a great loss with the untimely death of Harry Gisborne.

THE MUNITALP-FOREST SERVICE PROGRAM

In 1952 the Munitalp Foundation, Inc., under the technical direction of Schaefer, inaugurated a program of time-lapse photography of clouds with the objective of acquiring a series of movies which would show typical cloud formations in various parts of the world. As part of this program the cooperation of the U. S. Forest Service was sought since it was felt that mountain-summit fire-lookout stations would be excellent sites for obtaining such pictures. Several sites were selected in the national forests and parks of the Rocky Mountains. These were supplied with time-lapse movie units operated by local, relatively untrained personnel. An excellent series of cloud movies were obtained during that summer. The demonstration that good results could be achieved in this manner revived interest in the lightning-storm field study. As a result of discussions between Barrows and Jemison of the Forest Service and Schaefer of the Munitalp Foundation it was decided to establish a cloud survey in the national forests of western Montana, northern Idaho and eastern Washington.

The approach to the lightning-storm study of Project Skyfire emphasizes fundamental investigations of cloud types and structures and the related properties of the atmosphere such as moisture, nuclei, radiation, wind, and atmospheric electricity. Many of these data can readily be gathered at fire-lookout stations.

The facilities established for lightning research also provide opportunities for investigation of other meteorological problems associated with forest fires. Project Skyfire is concerned with questions such as the forecasting of strong winds; the relation of high clouds and jet streams to surface conditions; and the study of local winds and convection. An important facet of the field program is the development of new cloud-survey techniques based on the utilization of networks of key mountain-summit lookouts.

CLOUD MODIFICATION

Can lightning fires be prevented or reduced through cloud seeding? The final objective of Project Skyfire is to evolve some sort of practical weather-control method decreasing the incidence of lightning fires. In working toward this end it will be necessary to gain considerable quantitative knowledge of particular cloud-breeding spots in this area, of cloud heights and trajectories, of condensation and freezing nuclei counts, and of other factors which affect the growth of thunderstorms. In addition, analyses will be undertaken to show just how these factors are related to lightning. For such purposes the cloud survey will be continued and strengthened, and the mobile meteorological laboratory will be regularly employed. As with any rather fundamental research program the final objective is not the only goal; the measurements and analyses will also help give a better understanding of fire-weather and fire-behavior problems, and provide background for the investigation of characteristics of the jet stream.

Figure 8. Forest-fire lookouts are in a commanding position to observe and measure clouds.

II. THE CLOUD SURVEY

During the forest-fire seasons of 1953 and 1954 the Project Skyfire cloud survey was conducted from a network of fire-lookout stations (figure 8). In 1953 the survey was made from 25 stations in the northern Rockies. In 1954 the northern Rocky Mountain network was reduced to 17 stations (figure 9). Eight fire-lookout stations in California commenced cloud-survey operations during the latter part of the 1954 fire season.

CLOUD SURVEY OBJECTIVES

Clouds are dynamic indicators of weather. They are, of course, especially related to lightning. Clouds can be of assistance in studying wind movement, convection, and the moisture content of the atmosphere. Observation can show fairly well whether the cloud is composed of ice crystals or water droplets and whether the atmosphere is stable or unstable. Keen observation of clouds may assist in evaluating fire behavior (3).

The specific objectives of the Project Skyfire cloud survey are:

1. To observe, report, and map the development, movement and action of cumulus clouds, and high- and middle-level clouds.

2. To detect any cloud-breeding sites from which lightning storms may frequently develop.

3. To observe, report, and map lightning occurrence and intensity.

4. To obtain time-lapse motion pictures of clouds in selected areas.

5. To observe cloud action in relation to other atmospheric factors and especially to the weather factors influencing forest-fire danger.

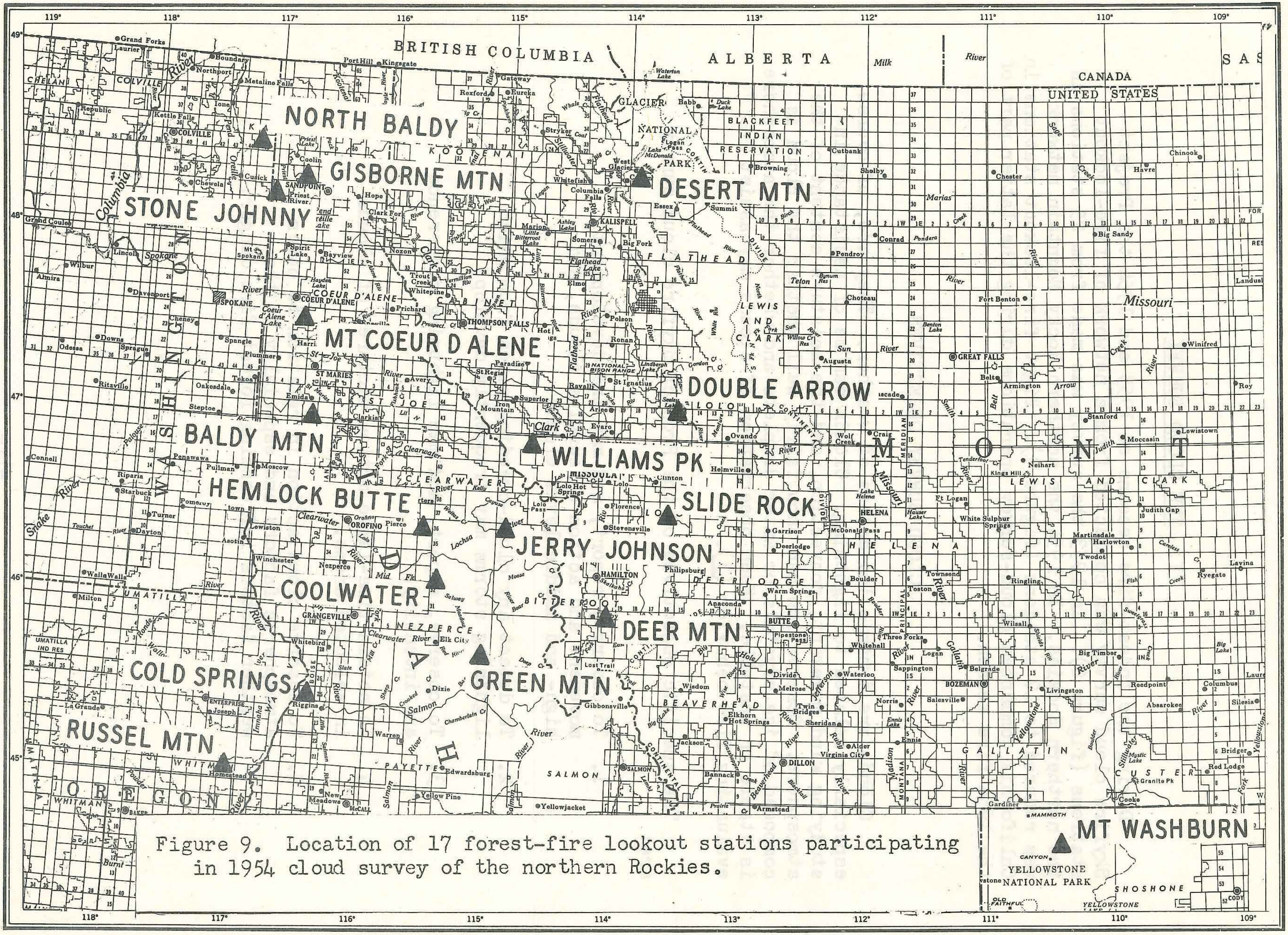


Figure 9. Location of 17 forest-fire lookout stations participating in 1954 cloud survey of the northern Rockies.

CLOUD SURVEY METHODS

Mountain tops are ideal locations for making cloud observations. As a general rule the area under observation covers a radius of 20 miles from the mountain summit although clouds may often be seen and identified at distances in excess of 100 miles. Thus each station observes an area somewhat in excess of 750,000 acres. The regions of observation from certain of the stations overlap slightly, for effective coverage.

During the summer of 1953, the Skyfire lookout observers were asked to fill in data every hour (oftener if needed) on a report form to record cumulus development, upper-cloud condition, and lightning activity. At specially designated times, the lookouts radioed or telephoned a "flash report" to give a picture of the cloud situation. At certain of the stations time-lapse movies were taken as the meteorological situation warranted.

For cumulus cloud types (figure 10), the information required every hour and at every major weather change was: type of cloud(s), direction and distance from the lookout, direction of cloud motion, and any pertinent notes. For upper-cloud conditions, information was recorded indicating the presence of cirrus, cirrocumulus, altocumulus lenticular, or altocumulus billow clouds, a rough plot of where the upper clouds existed around the station, a check if the clouds extended horizon to horizon, the direction of cloud motion and their speed (fast or slow), and the surface wind direction and speed. For lightning activity, the number of strikes, time, and direction were requested. During a typical day, three or more pages of data would be accumulated from each lookout observer.

Measurement apparatus at the lookouts consisted mainly of a firefinder, a circular map table on which was mounted a rotating azimuth indicator (figure 11). Some of the firefinders also had provision for measurement of elevation. The eaves of the lookout station, however, prevented the use of the firefinder on any clouds except those at low angular elevations.

Of the data gathered, the most precise appear to be the locations of the first cumulus clouds. The lookouts encountered various problems in filling out the forms, and the training and followup were not adequate to rectify all troubles completely. Therefore interpretation of a considerable portion of the data was difficult. In order to obtain better data and ease the work of the lookouts, the survey techniques were considerably altered for the 1954 project as a result of the 1953 experiences. For the 1954 cloud survey the following preparations were made:

1. A cloud-observation manual was prepared to provide reference material to supplement the school and followup training. The manual

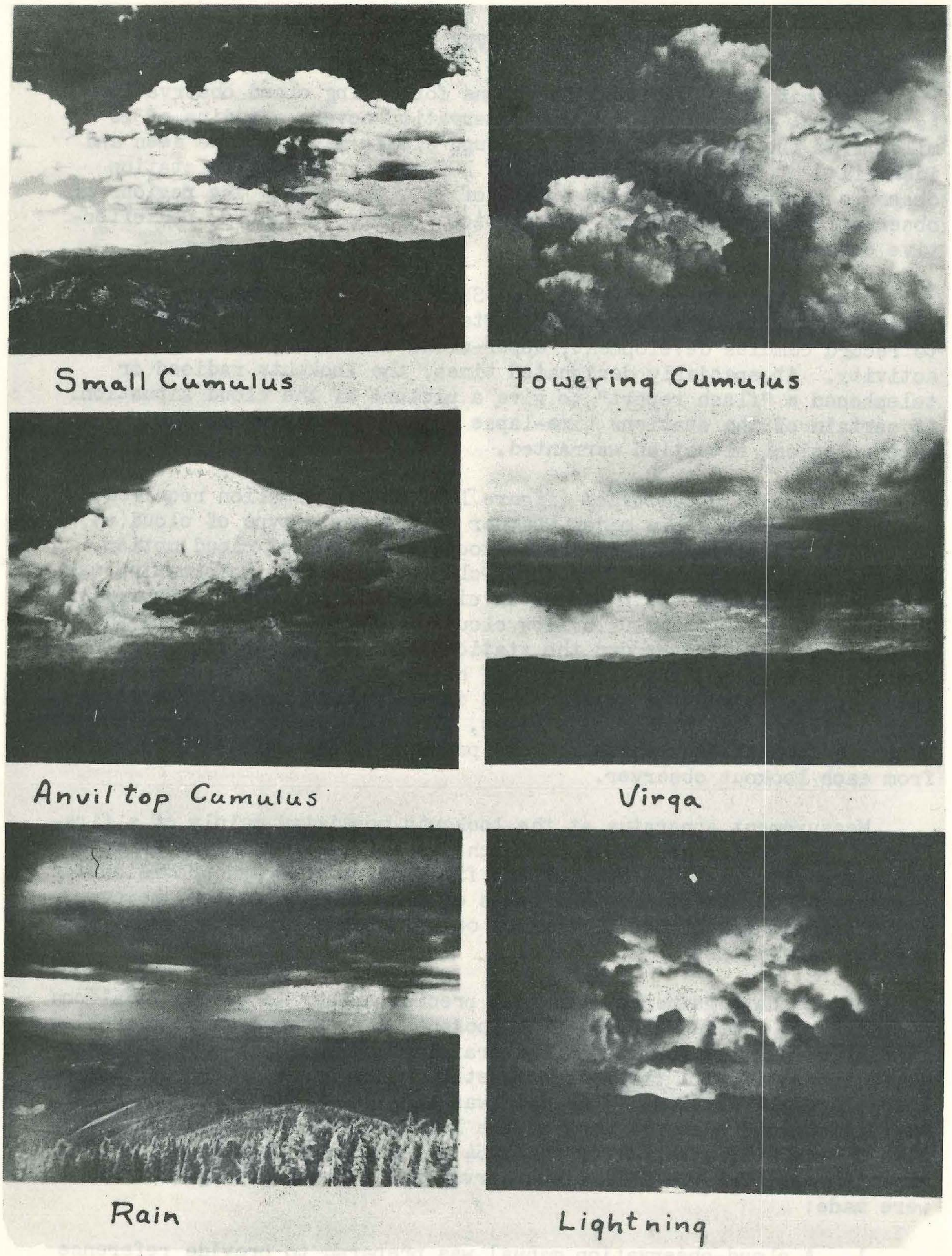


Figure 10. In the cloud survey, fire lookouts record the action of cumulus clouds from their initial formation through all advanced stages that occur.

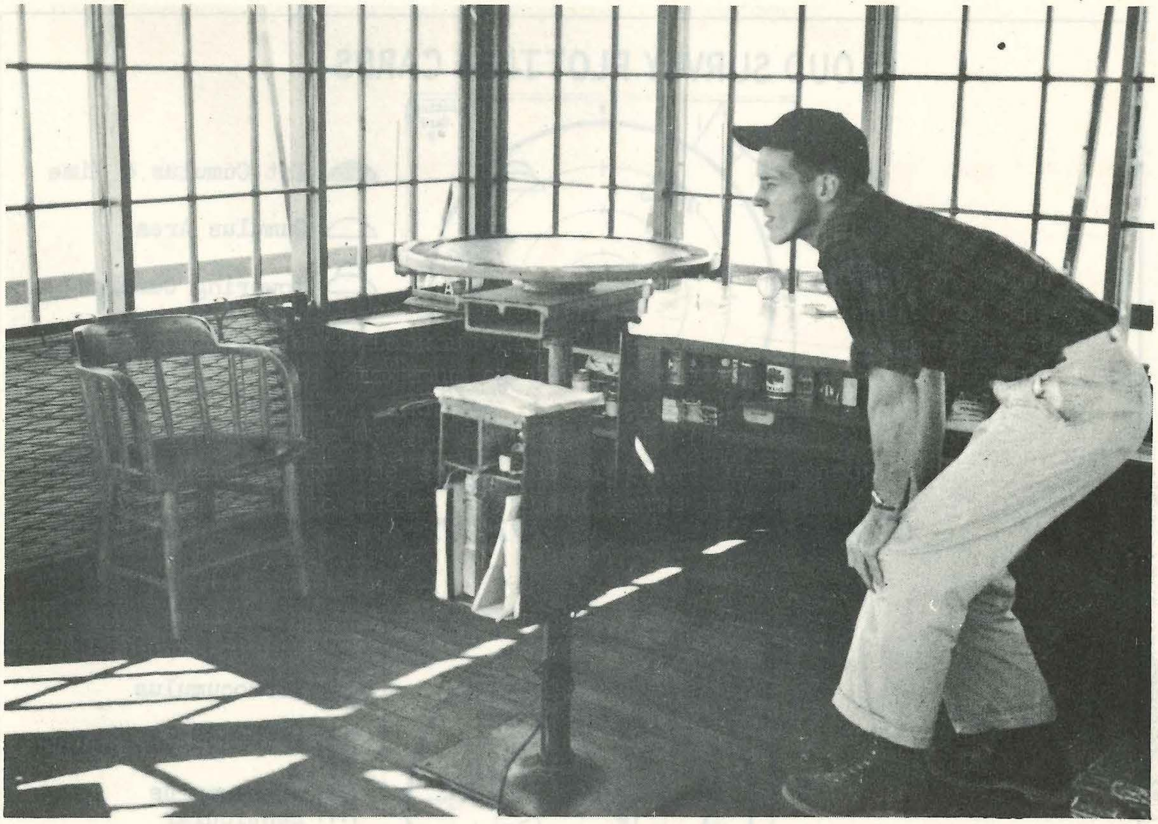


Figure 11. The firefinder used to locate forest fires is also useful in determining the general location of clouds.

described simple techniques for cloud measurements, and discussed the appearance, development, and characteristics of cumulus and upper clouds. It gave photographic examples of the types of middle and high clouds to be identified in the survey.

2. A more detailed operations guide was drawn up, instructing the lookouts in their daily duties.

3. Much of the survey information was put on cards, on which a 1-inch-radius circle represented the area within 20 miles of the mountain summit. Each lookout daily prepared (a) a card showing the first cumulus and the maximum cumulus activity, (b) a card showing all lightning activity, and (c) three cards showing the upper-cloud condition at 0800, 1200, and 1600 M. s. t. (figure 12). Each lookout marked the cards with the same type of pen. The appropriate cards were later affixed to analysis maps (figure 13).

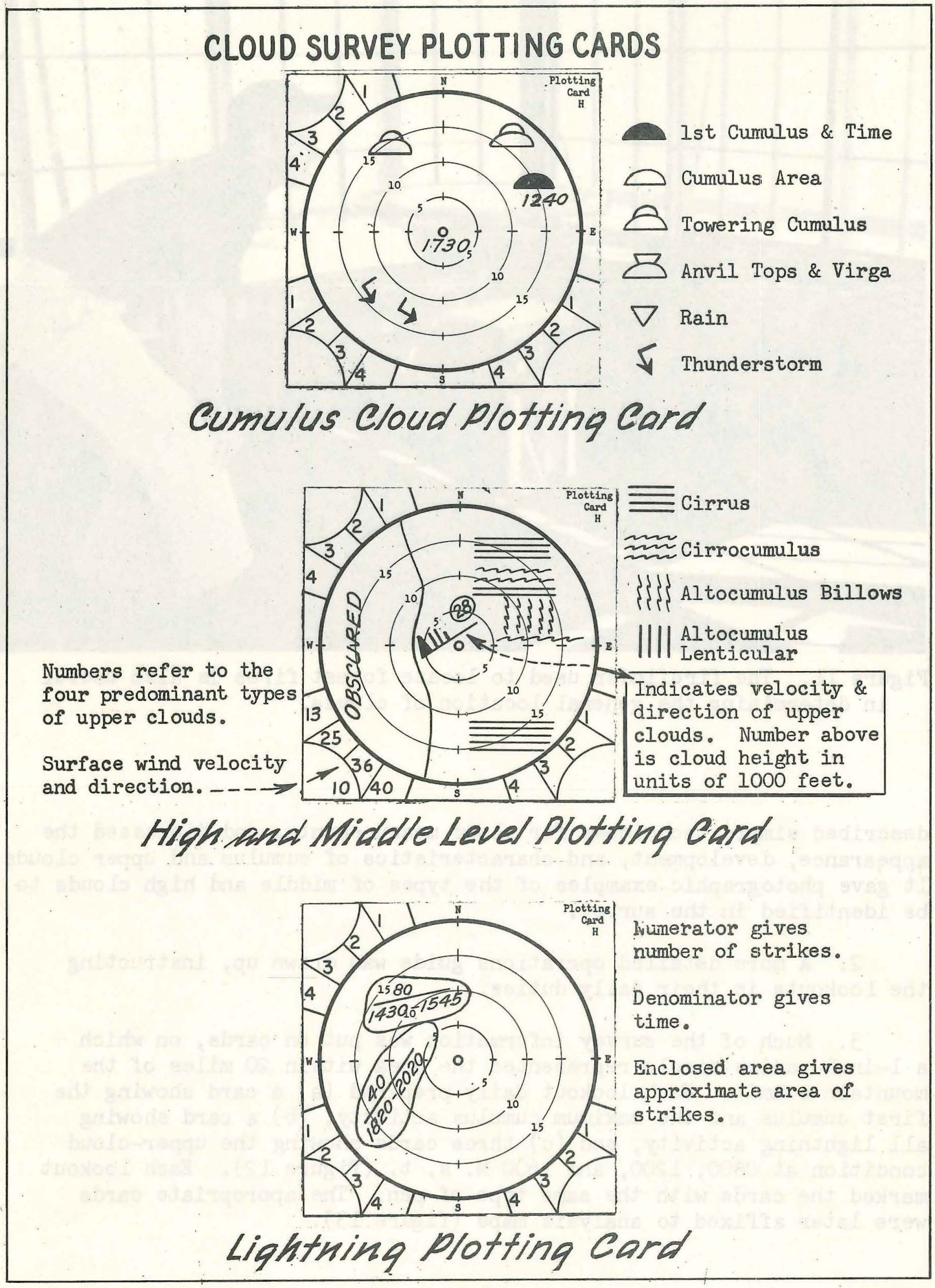


Figure 12. Plotting cards are filled out at lookout stations and are later pasted on analysis maps.

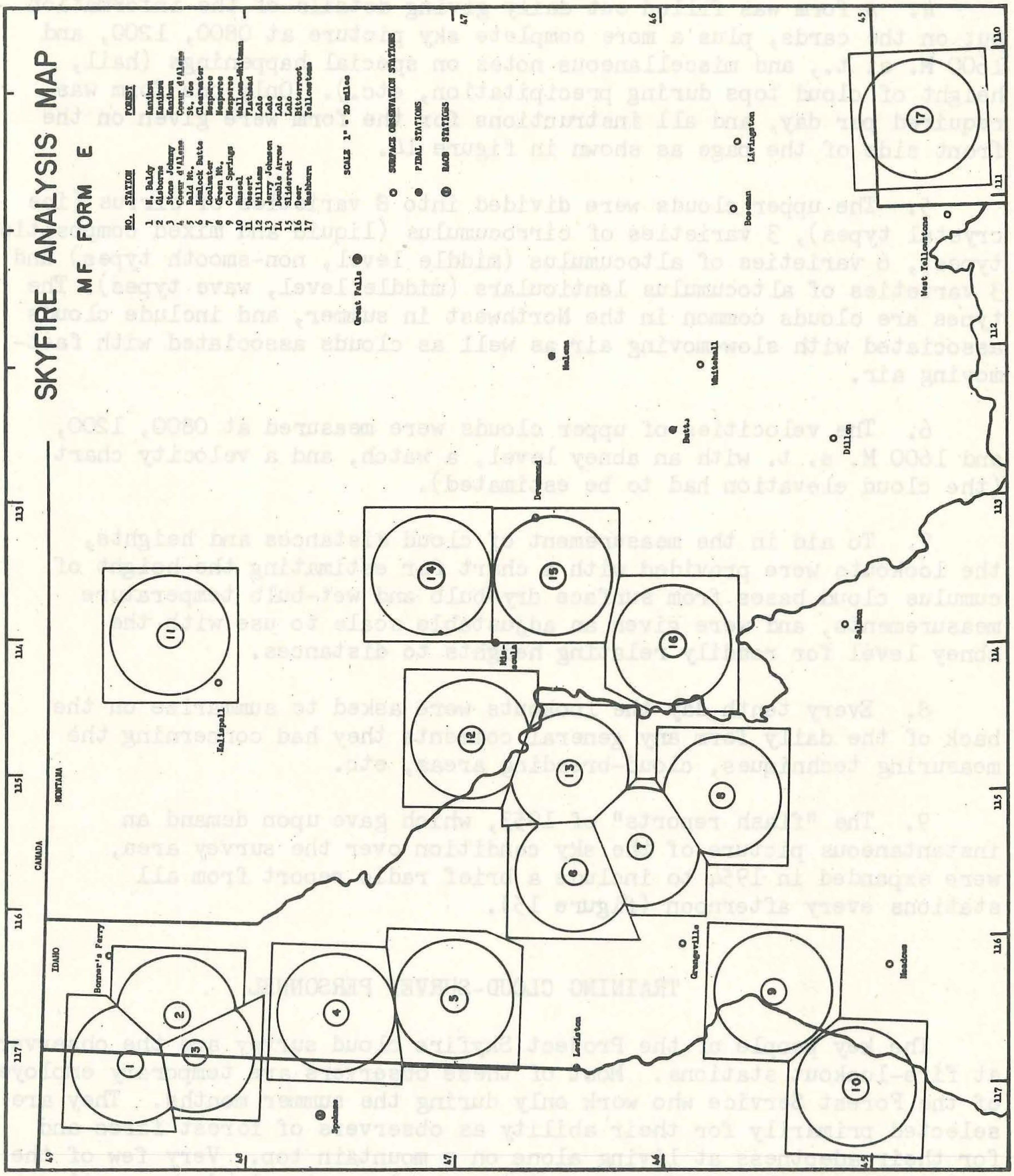


Figure 13. Analysis map on which plotting cards of clouds and lightning are affixed.

4. A form was filled out daily giving details of the information put on the cards, plus a more complete sky picture at 0800, 1200, and 1600 M. s. t., and miscellaneous notes on special happenings (hail, height of cloud tops during precipitation, etc.). Only one form was required per day, and all instructions for the form were given on the front side of the page as shown in figure 14.

5. The upper clouds were divided into 8 varieties of cirrus (ice crystal types), 3 varieties of cirrocumulus (liquid and mixed composition types), 6 varieties of altocumulus (middle level, non-smooth types) and 3 varieties of altocumulus lenticulars (middle level, wave types). The types are clouds common in the Northwest in summer, and include clouds associated with slow-moving air as well as clouds associated with fast-moving air.

6. The velocities of upper clouds were measured at 0800, 1200, and 1600 M. s. t. with an abney level, a watch, and a velocity chart (the cloud elevation had to be estimated).

7. To aid in the measurement of cloud distances and heights, the lookouts were provided with a chart for estimating the height of cumulus cloud bases from surface dry-bulb and wet-bulb temperature measurements, and were given an adjustable scale to use with the abney level for readily relating heights to distances.

8. Every tenth day the lookouts were asked to summarize on the back of the daily form any general comments they had concerning the measuring techniques, cloud-breeding areas, etc.

9. The "flash reports" of 1953, which gave upon demand an instantaneous picture of the sky condition over the survey area, were expanded in 1954 to include a brief radio report from all stations every afternoon (figure 15).

TRAINING CLOUD-SURVEY PERSONNEL

The key people of the Project Skyfire cloud survey are the observers at fire-lookout stations. Most of these observers are temporary employees of the Forest Service who work only during the summer months. They are selected primarily for their ability as observers of forest fires and for their adeptness at living alone on a mountain top. Very few of the lookout firemen have had any previous experience in cloud observation. Therefore, training of the observers in cloud identification and the fundamentals of cloud action is an essential part of the cloud-survey program.

In 1953 and again in 1954 a special 3-day training school was held for all personnel in the cloud-survey network. These schools stressed identification of cumulus clouds, and high- and middle-level clouds. The lookout observers were also given instruction in measuring cloud heights and speeds, use of the firefinder in cloud location,

FORM 6
RF - INT
PREVENTION
Project Skyfire

STATION NUMBER 14
STATION NAME Double Arrow
DATE: DAY 15 MONTH July 1954
OBSERVER Dorothy Taylor

INSTRUCTIONS: ALWAYS FILL IN ALL SPACES, USING A DASH "-" IF NO NUMBER OR LETTER IS APPROPRIATE. USE 0 TO DENOTE SKY CLEAR OF CLOUDS IN THE PARTICULAR CATEGORY. USE 9 TO DENOTE CLOUDS OBSCURED. A WIGGLY LINE UNDER A NUMBER MEANS THE NUMBER IS VERY QUESTIONABLE. CONSIDER 20 MILE RADIUS.

0800, 1200, & 1600 WEATHER RECORD

CUMULUS CONDITIONS

Fill in second and third lines for each observation time, as required by cumulus types and areas.

MOST ADVANCED CUMULUS TYPE
1 Cumulus
2 Towering Cu
3 Anvil tops
4 Virga
5 Rain
6 Thunderstorm

AZIMUTH (DEGREES) TO LEFT EDGE OF CUMULUS OR CUMULUS AREA

AZIMUTH TO RIGHT EDGE. CIRCLE IF AZIMUTHS REFER TO INDIVIDUAL CLOUD

ESTIMATED VELOCITY OF CLOUD MOTION (MPH)

DIRECTION FROM WHICH CLOUDS MOVE

DISTANCE (MILES) TO NEAR EDGE OF CUMULUS

SURFACE CONDITIONS

VELOCITY OF SURFACE WIND (MPH)

DIRECTION FROM WHICH SURFACE WIND BLOWS

WET BULB TEMPERATURE

DRY BULB TEMPERATURE

UPPER CLOUD CONDITIONS

HEIGHT (IN UNITS OF 1000') USED TO FIND VELOCITY. CIRCLE NUMBER IF VELOCITY IS ACCURATELY MEASURED. USE X IF VELOCITY CANNOT BE ESTIMATED.

VELOCITY AT HIGHEST CLOUD LEVEL (MPH)

DIRECTION FROM WHICH CLOUD MOVES

11 Rippled smooth Ci
12 Thin wispy Ci
13 Thick wispy Ci
14 Patterned Ci
15 Hooked Ci
16 Filaments of Ci
17 Coherent Ci
18 Straight bands of Ci

24 Liquid cloudlet Cc
25 Liquid patterned Cc
26 Decaying Cc

31 Patternless Ac
33 Rect. Ac cloudlets
34 Rect. Ac cloudlets with ice streamers
36 Ac billows
37 Coherent Ac billows
38 Ac cloudlets arranged down-wind

45 Standing wave Ac
46 Moving wave Ac
47 Coherent waves of Ac

MST Time	Type	Dir.	Vel.	Az(L)	Az(R)	Dist.	T_d	T_W	Dir.	Vel.	Dir.	Vel.	Height	Ci	Cc	Ac	Acl
0800	2	W	10	250	200	13	70	60	-	0	S	60	20	10	20	38	45
0800							NOTES 0800 & EARLIER										
0800																	
1200	6	W	8	overhead		0	72	61	SE	5	SW	X	30	14	29	39	49
1200							NOTES 0800-1200 Rain NW 6 Mi. at 11:45; first thunder 11:53. Some hail 1205; also light rain.										
1200																	
1600	5	W	10	204	214	12	64	56	N	14	-	-	-	19	29	39	49
1600							NOTES 1200-1600 Rain from another cloud 1313; no lightning. From still another at 1600 at 2100; still no lightning.										
1600																	

LIGHTNING ACTIVITY

TIME OF START (MST)	TIME OF END	NUMBER OF STRIKES	AZIMUTH TO LEFT EDGE OF ACTIVITY	AZIMUTH TO RIGHT EDGE. CIRCLE IF WITHIN 10 MILES
None seen, though thunder heard.				
2200	2314	8	210	120

SPECIAL ITEMS

Note when and where rain begins. Note if lightning or thunder occurs without any rain. Note any unusual happenings (hail, severe surface wind over 30 mph, much cloud-to-cloud lightning with no strikes, odd motions of vapor trails, etc.). If rain occurs without lightning, try to measure the heights of cloud tops.

TIME	
11:45	Rain began 11:45; at 1208 it was at L.O. with small amount of hail; not much thunder - no cloud to ground strikes. After cloud passed E, took its height when rain was falling on Mt. 10 miles distant. 35,200. (Took color picture including top and rain).
2200	Much cloud-to-cloud lightning, very brilliant near L.O.; dashing rain at 2210 - 2230.

If more space is needed, use the rear of this form. On July 9, 20, 30, August 10, 20, 30, and final day of observations, on the rear write any general notes which you consider helpful (best breeding areas, distances and azimuths, storm courses, observation difficulties, etc.).

Figure 14. Form filled out each day at cloud-survey stations.

Figure 15. Radio communication enables forest-fire lookouts to furnish the Skyfire analysis center with pertinent information on clouds and lightning.

operation of fire-weather stations, and radio-transmission procedures. Much of the training school program was held right at a lookout station where practical cloud-survey operations could be reviewed. Motion pictures and colored slides of clouds were used as aids in cloud-identification training.

Experience has shown that on-the-ground instruction of observers must supplement the more or less formal program of the special training school. Followup training sessions at each lookout station are essential in the development of competent observers. During the fire season some members of the Skyfire staff are continuously engaged in visiting lookout stations in the cloud-survey network. The daily radio reports keep the staff in touch with the lookout observers and often indicate the stations where additional training is most needed. Followup visits to lookout stations also are important in maintaining the teamwork and esprit de corps so important in an undertaking of this nature.

CLOUD ANALYSIS

The compilation of cloud-survey data is a means to an end, not an end in itself. For value, the observations must be related to larger scale synoptic situations. In 1953 a rough first attempt was made to "type" or explain the weather patterns causing lightning. In 1954 the U. S. Weather Brueau provided personnel and facilities for improving the analysis. This phase of the cloud survey is a most important one, and will be receiving a larger percentage of the research effort as Project Skyfire continues.

TIME-LAPSE PHOTOGRAPHY

The system of time-lapse motion-picture photography developed by the Munitalp Foundation provides an excellent means of studying cloud action. In most Project Skyfire operations 16-millimeter cloud photographs are taken at 2-second intervals and then projected at normal speed. This speeds up the motions in clouds about thirtyfold so that an hour of action can be displayed in approximately two minutes of film-projection time. The time-lapse principle enables dynamic cloud action to be seen in a manner not possible with the naked eye. The cloud factors associated with many different weather situations and many types of lightning storms can be recorded on film for detailed analysis.

The equipment used in the time-lapse-photography program is rugged enough for continuous field use and simple enough to operate to insure good results from relatively untrained photographers (figure 16). The automatic-shutter operation on a standard 16-millimeter motion-picture camera is accomplished by a relay which is actuated at the relaxation time of a capacitor-relay circuit. Power is provided by a 45-volt B battery. The camera is mounted on a sturdy tripod (figure 17). Other equipment used in the photography program includes an exposure meter, a protractor for measuring camera angle, and a title board for labeling essential data on each roll of film. Color film has been used for virtually all of the photography.

During the fire seasons of 1952, 1953, and 1954 over 6000 feet of time-lapse motion pictures have been obtained from 12 stations in the northern Rockies. Usually there have been at least four time-lapse motion-picture cameras operating simultaneously during interesting meteorological situations. As a result, regional storms can be photographed to show variations by location and time. The photography of clouds associated with the jet stream has provided an excellent means for studying the motions and shapes of high- and middle-level clouds. Time-lapse photography has been found to aid in detecting the areas where cumulus clouds first form and grow.

Figure 16. The Munitalp time-lapse motion-picture equipment used at fire-lookout stations for cloud photography.

Figure 17. Time-lapse motion-picture cameras mounted on the catwalk of forest-fire lookout stations are in an ideal position to record the life cycle of clouds and lightning.

An important phase of the time-lapse photography program is the use of a "sphere" camera for detailed studies of cloud-breeding areas. This camera photographs the sky through a standard, inexpensive, spherical flask filled with water. The system enables 112° of sky to be photographed from a fixed position of the camera. During 1953 the "sphere" camera was used at Gisborne Mountain in the Priest River Experimental Forest (figure 9). In 1954 the camera was used at Cold Springs Lookout in the Nezperce National Forest to photograph the day-by-day life cycle of clouds which form in the adjacent Wallowa Mountains (figure 9).

The results of the time-lapse photography program show that forest-fire lookout stations are ideal places for the operation of cameras. The commanding view of clouds and mountains and the constant availability of an operator provides about the best possible site for photographic work. A good start has been made on the building of a photographic record of cloud types and action in northern Rocky Mountain skies.

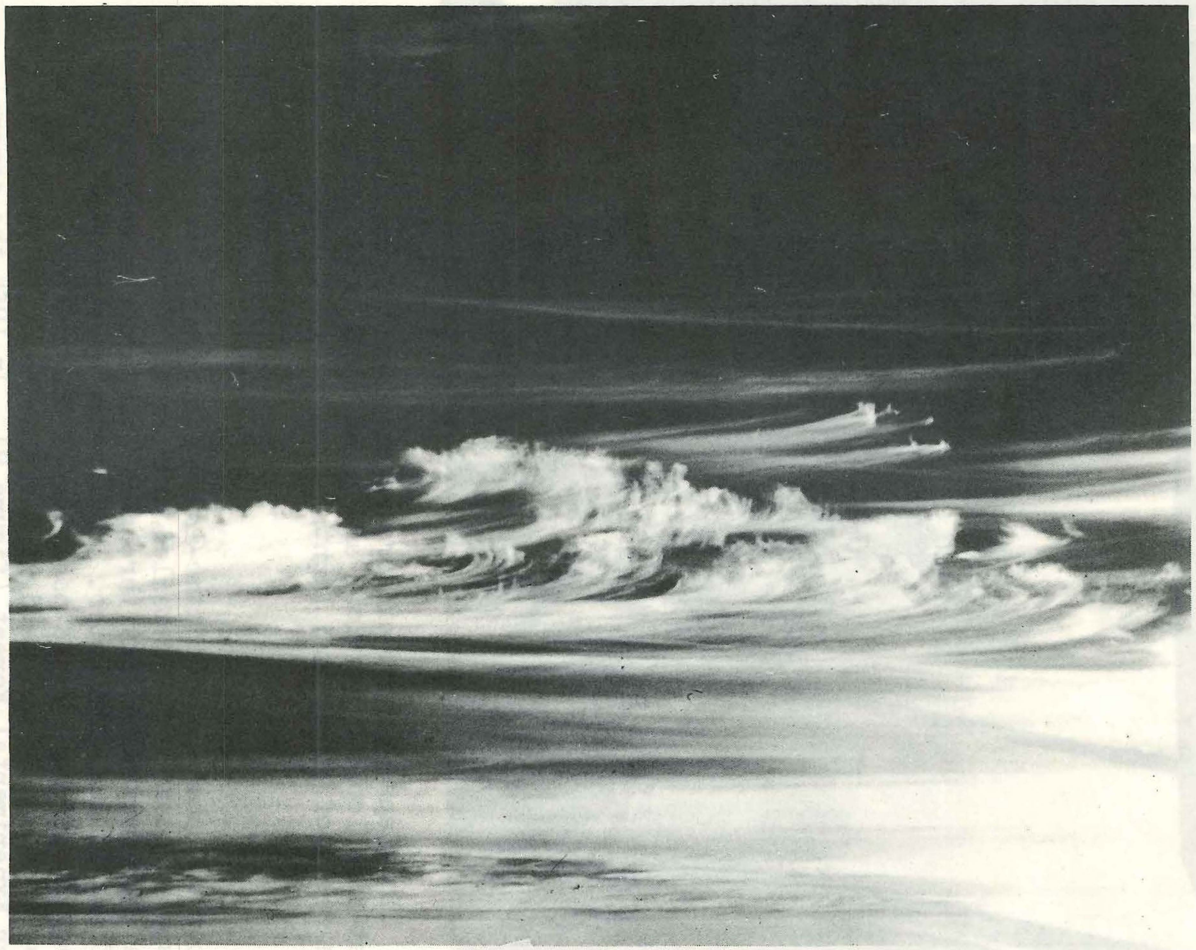


Figure 18. Spectacular clouds, such as these cirrus "streaks," are often associated with the jet stream.

III. STUDY OF THE JET STREAM

The jet stream can best be visualized as a flat, wide, river of air, flowing on a meandering course, generally from west to east, with a central axis of peak velocity winds at 20 to 40 thousand feet above sea level. Observations made to date indicate that one or more jet streams are usually present during the fire-season months either over the northern Rocky Mountain region or just north or south of the area.

Many unknown facts about jet streams remain to be discovered. However, from the information now available, it is clear that any research of lightning and associated atmospheric factors must consider possible relationships to the location and character of jet streams. There is strong evidence that certain high- and middle-level clouds are frequently associated with a jet stream (figure 18). There are also indications that important relationships may exist between a jet stream and the character of lightning storms, as well as the general character of the pre- and post-storm weather influencing the behavior of lightning fires. The jet stream means a strong vertical wind shear, which may tend to blow the tops off towering cumulus clouds and thus hinder them from reaching lightning-storm proportions. In other situations the jet stream appears to make the storm worse.

IDENTIFICATION OF THE JET STREAM WITH CLOUDS

The best way to determine the location of the jet stream by clouds is to note the velocity of airflow as evidenced by cloud motions. This is impossible to do from moving aircraft and difficult from the ground. A second technique is to watch for certain cloud types; forms of cirrus, cirrocumulus, altocumulus lenticulars, and altocumulus billows tend to be associated with the jet stream (13, 14). These 4 types were recorded by the 25 lookout observers in Project Skyfire in July and August of 1953 (figure 19). Direction of cloud motion, cloud velocity, coherence, and surface winds were also noted hourly, and during each observation a rough picture of the cloud positions was sketched. All the data compiled by the lookouts were plotted on area maps for 0800 and 1400 M. s. t. daily, and compared with the position of the jet stream as derived from the U. S. Weather Bureau 300 mb. and 500 mb. charts.

During the 124 observation times of summer 1953, the jet stream was within the region 67 times, and outside or missing 57 times. The following results were obtained:

Jet Stream Present	Ci, Cc, Acl, or Acb Clouds Present	Percent of Instances
No	No	31
Yes	Yes	30
Yes	No	16
No	Yes	23

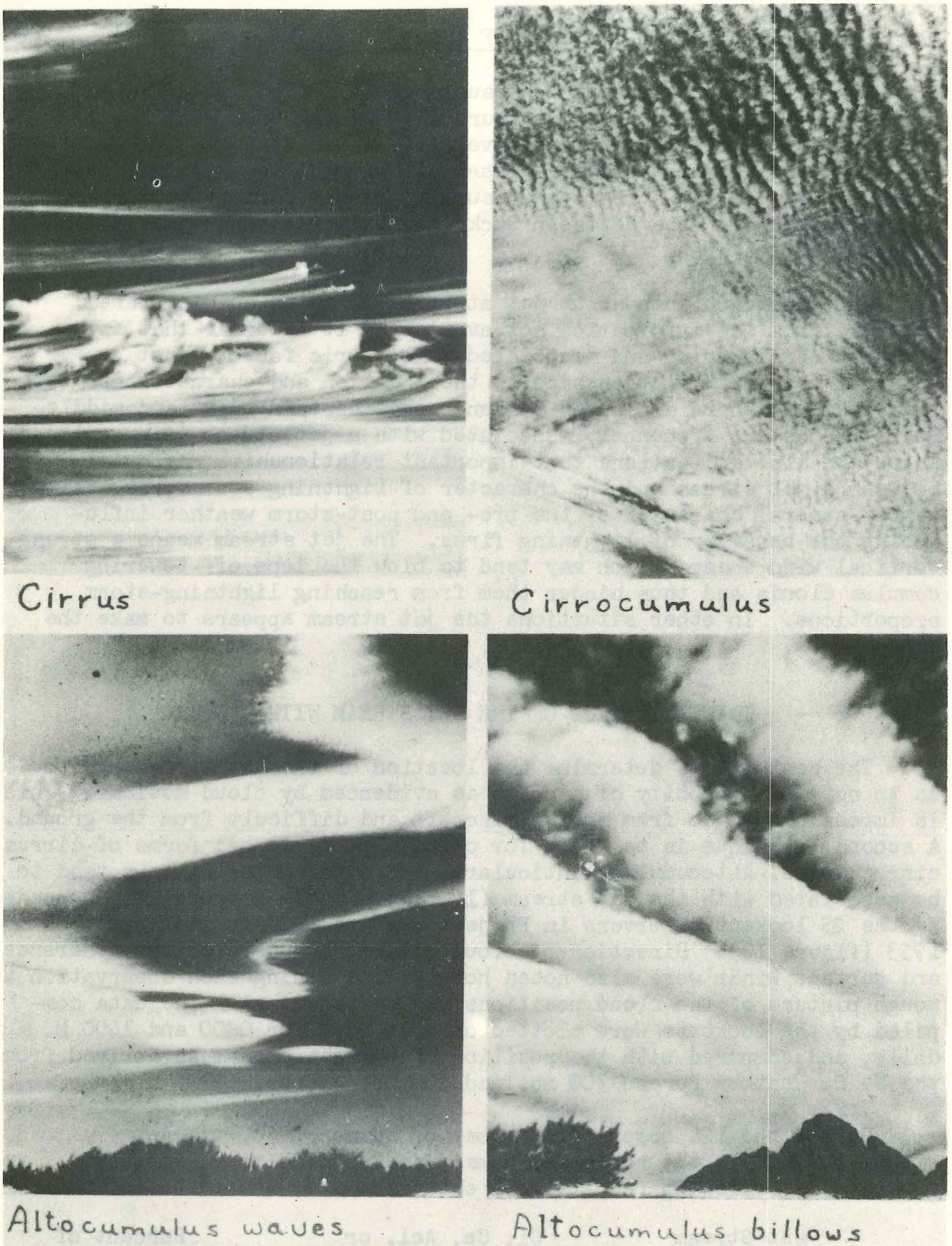


Figure 19. Four high- and middle-level cloud types often associated with the jet stream.

There was no very definite tendency for the clouds to appear on the north side of the jet stream instead of the south, or vice versa.

In 61 percent of the cases the special cloud-association method was successful; no clouds = no jet stream, clouds = jet stream. In 16 percent of the cases the jet stream was present but the air aloft was so dry that there were none of the upper clouds present. In 23 percent of the instances (mostly from August) there was no jet stream but the "associated clouds" (usually several types) were observed. These "failures" may be inherent in the system, but certain other factors certainly contribute to them:

1. The U. S. Weather Bureau 300 mb. network is so sparse that jet stream flows could be present but unobserved on the charts. This might explain some cases, but not many.

2. During the first summer of Skyfire field observations much of the data were not complete and also many bits of evidence had to be discarded due to ambiguity. False cirrus from thunderstorm anvils were undoubtedly often reported as cirrus indicating the jet stream.

3. In most cases of "clouds but no jet stream" there was a low-pressure center about 900 miles off the United States-Canada border, bringing in moist air aloft from the southwest. Slight vertical motions would form clouds in such air. Half of the "clouds but no jet stream" cases were associated with surface or upper fronts, where extra lifting would be expected.

4. The slow-moving clouds were often reported in the diverging-fan area where a jet stream slowed down and lost its identity, or in the corresponding converging area; also they were observed in the slow-moving air close to closed lows with high winds. In many of these cases, although the air in which the clouds existed was slow moving, it had probably been recently in a true jet stream.

5. The mere presence of high- and middle-level clouds is not uniquely related to the jet stream, since moisture and lifting derive from many causes. During the lookout-training course little stress was laid on separating the "fast-looking" clouds from the "slow-looking" type; in fact, only illustrations of the "fast-looking" types were shown. This omission was probably the biggest factor in the "clouds but no jet stream" cases.

During the summer, clouds indicated the jet stream 65 percent of the time it was present. If the additional cases of "clouds but no jet stream" can be avoided by more careful examination of the detailed cloud structure, the whole scheme of jet-stream location by cloud observations can be termed successful. During the winter in this area when the jet stream is twice as fast as during the summer, and in other regions of consistently greater jet-stream speeds, the cloud-identification method should prove even more useful.

ESTIMATING WIND VELOCITY BY CLOUD APPEARANCE

Schaefer has indicated how fast-moving cirrus, cirrocumulus, altocumulus lenticular, and altocumulus billows tend to be the clouds associated with the jet stream (14). Analysis of the cloud-survey data has shown that a further refinement or typing might be employed in order to make location of the jet stream easier from cloud observation: the cloud types should be subdivided into those indicative of high velocity and those indicative of low velocity. Since the cloud texture or microstructure is somewhat independent of air-mass moisture, it will provide a better jet-stream indicator than will merely the presence of certain clouds.

The study of heated fluids in the laboratory, of air currents over the ocean, of alto-level clouds, of wind over sand, and of other natural phenomena has shown a tendency for (1) very small shear to be associated with regular rectangular or hexagonal flow patterns, (2) moderate shear to be associated with transverse waves, (3) strong shear to be associated with longitudinal waves or rolls, and (4) very severe shear to be associated with turbulence, no regular flow. Therefore, the characteristics of certain cirro and alto clouds in jet-stream conditions would be expected to indicate wind shear, and vice versa. Wind shear is related to total wind velocity and is ordinarily in the same direction.

Approximately 60 color and 150 black and white cloud pictures were taken between July 1 and October 1, and compared with cloud velocities measured by the abney-level method. In the preliminary analysis, it was found that cirrus clouds were observed, alone, at 90 knots and 7 knots, altocumulus billows were found between 90 knots and 25 knots, cirrocumulus were present at 70 knots to 20 knots, and altocumulus lenticulars appeared moving 85 knots as well as 25 knots. The combination of any 2 or more of the 4 types likewise did not prove to correlate especially well with velocity.

When a speed factor was given to the appearance of the clouds in each photograph, the correlation with velocity improved greatly. The cirrus were fast moving when they were drawn out into long lines parallel to the wind, by wind shear. They were slow when their structure was weak and random, showing no preferred direction. Of the cirrocumulus, the clouds with the most definite wavelet patterns were the fastest. The fastest altocumulus types were those with pronounced orientation of the cloudlets, either parallel or perpendicular to the wind. The shapes of altocumulus lenticulars depend mostly on ground configuration and so would not be strongly related to wind speeds, but the waves produced by the fastest winds tend to have the sharpest edges and the smoothest texture.

The speed factors were considered when the cloud types for the 1954 lookout training school were established. In effect, each of the four main categories was subdivided into types representative of

different speed ranges; the typing involved elongation, microstructure (or texture), and composition as well as the ordinary cloud-type considerations. The rules can certainly be improved with time, and still be simple enough to be of practical value even for the weak jet streams in the summer in this area.

SURFACE WINDS AND THE JET STREAM

With the small amount of data available it is difficult to generalize on the relationship between surface winds and the jet stream. The mountain winds due to convective heating, the local downdraft outflow of the thunderstorms, and frontal winds may all exceed 25 knots. On the other hand, surface winds below the jet stream may sometimes be very light. However, surface winds greater than 35 knots over an extended distance seem due solely to a jet-stream effect. These winds are doubly dangerous from the fire-danger standpoint because they may occur in dry weather.

During the morning of August 24, 1953, the wind at Salmon Mountain Lookout reached 70 knots; this was directly below the axis of a 70-knot jet stream and in a cold front occlusion situation. Snow, sleet and hail were also reported. The 300 mb. and 500 mb. U. S. Weather Bureau maps showed the velocity was roughly the same at those two levels. This was the maximum wind reported during the cloud survey.

Few of the cloud-survey stations regularly reported the surface winds. The small amount of data available for 0800 and 1400 M. s. t. did show that winds over 25 m. p. h. were almost invariably associated with a jet-stream condition. The 1700 M. s. t. winds were also checked daily at three stations. The maximum 1700 winds, 29 to 43 m. p. h., were recorded on 5 days; a jet stream was overhead 4 of these days, and a frontal situation existed the other day.

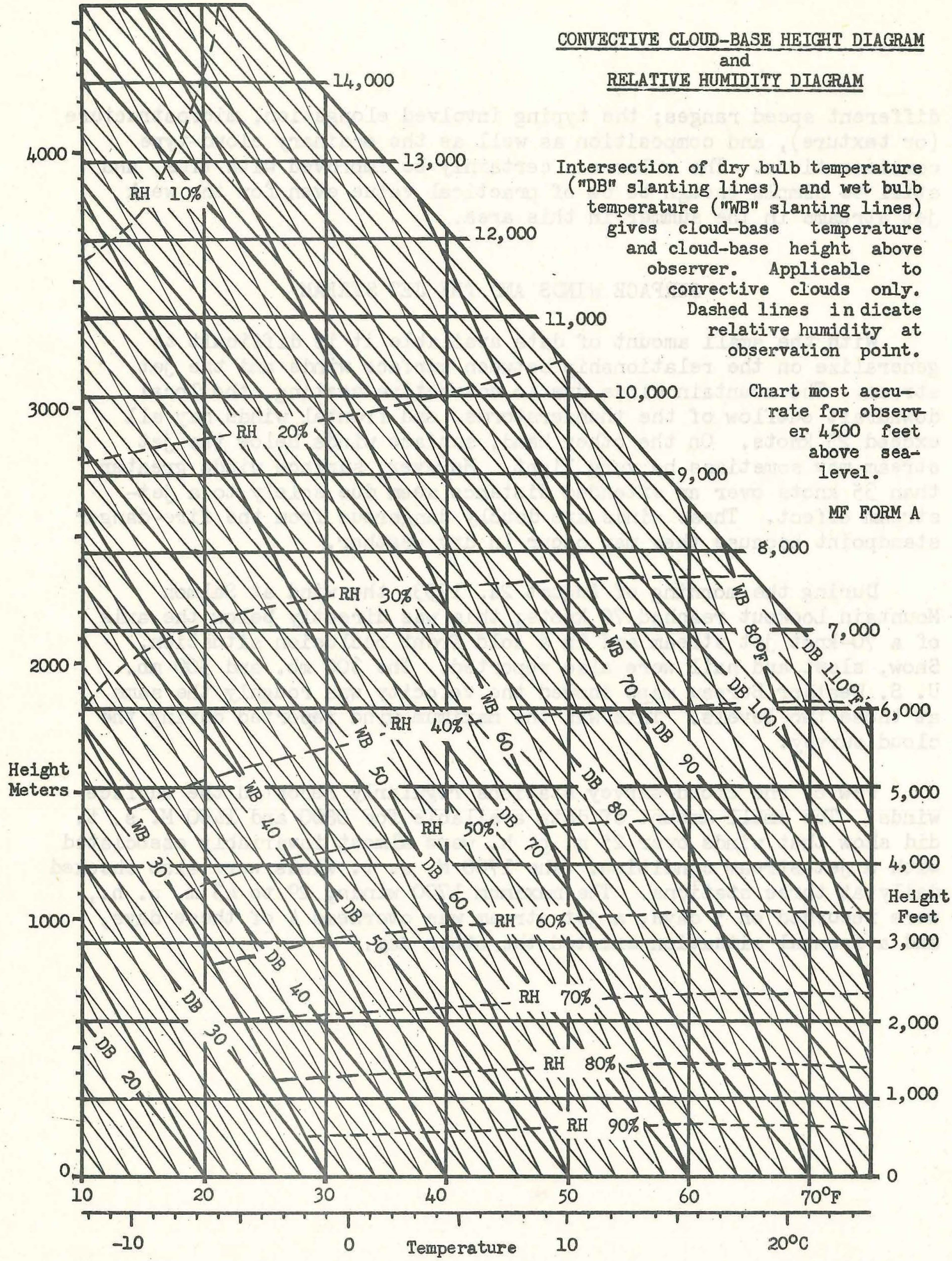


Figure 20. Diagram used in calculating cloud-base height.

IV. SPECIAL STUDIES

The research program of Project Skyfire has called for the development of special tools and research techniques. Also there has been a need to explore the theory of cloud development, the lightning mechanism, and atmospheric electricity. These studies facilitate the general aims of the over-all project. For convenience in reporting they are grouped under the heading of special studies.

WEATHER TYPES AND LIGHTNING

All lightning occurrences in the survey area during July and August 1953, were examined to ascertain the corresponding synoptic pictures. In 1953 there was more lightning than average and there were more frontal passages.

Four frontal weather types were considered, and three air-mass types. The division of lightning storms into types is not simple, since a specific instance rarely fits into one type. Frontal types are differentiated from air-mass types by consideration of whether the vertical motions were mechanically or thermally induced, and yet the activity of fronts does depend strongly on thermal instability and diurnal timing, and the instability of an air mass is strongly affected by the advection of cold air aloft. Understanding the synoptic situation corresponding to lightning occurrences is an important phase of future Project Skyfire work; this preliminary typing served to point out the problems and permit a few generalizations to be made.

There were 15 frontal cases and 13 air-mass cases producing lightning in the summer of 1953. On probably only three occasions did storms begin without surface air reaching the clouds. Therefore cloud seeding with ground generators might affect a large majority of the storms.

CONVECTIVE CLOUD-BASE HEIGHT FROM DRY-BULB — WET-BULB TEMPERATURES

It is possible to get a rough estimate of the elevation of the base of a convective cloud by measuring the dry- and wet-bulb air temperatures at ground level. Figure 20, MF Form A, permits these rapid height calculations, and at the same time gives the cloud-base temperature and the relative humidity of the surface air. This chart is based on the assumption that the cloud base is the same as the "lifting condensation level," i.e., the level at which condensation begins in the dry, adiabatically lifted air parcel.

If the air parcel that is sampled has the same properties as the air that is forming the cloud, accuracy will be good. In hilly terrain the cumulus clouds tend to form from air heated over the hills; thus a fire lookout is in a good position to sample appropriate air to find the height of cloud bases near the lookout station.

If the moisture content of the air on hilltops and in valleys is the same, the extra heating of the hills will result in higher cloud bases than those bases due to valley air. Experiments have verified this effect; bases as calculated from Gisborne Mountain Lookout averaged about 1400 feet higher than bases calculated from the Priest River Experimental Forest headquarters (3140 feet below Gisborne Mountain Lookout). Presumably the higher bases were the more correct. An obvious rule to correct valley readings to hilltop conditions would therefore be to add, to the valley-calculated cloud height, one-half of the height of appropriate hills above the valley. Many factors contribute to the valley-hilltop differences and so such a simple correction can be but a rough first approximation. The elevations of cloud bases differ over a region and even from cloud to cloud. Glider pilot reports verify that the higher bases are associated with the stronger upcurrents obtaining their energies from mountain heating.

At the Priest River Experimental Forest during a warm mid-afternoon, consecutive temperature measurements at 8-minute intervals yielded cloud-base heights of 8350, 9000, 9280, 8550, 8900, 8970, 8700, 8900, and 9120 feet above ground; these values illustrate how local conditions change rapidly, and demonstrate some of the inaccuracies of the method. They show why there is no need to read the temperatures more accurately than to the nearest degree.

The dry-bulb and wet-bulb measurements may conveniently be taken with a small sling psychrometer. Tests with this device show that 250 swings will bring the temperature readings to within about one-tenth of a degree F. of the true ones.

MF Form A (figure 20) has been compiled by using (a) the change of dewpoint with elevation shown on U. S. Weather Bureau Form 113E, (b) the dry adiabatic lapse rate indicated on Form 1147B (revised December 1950) which differs from that on the older U. S. Weather Bureau Form 1113E, (c) dewpoints and humidities from the table supplied by the U. S. Forest Service for elevations between 3800 and 6000 feet above sea level. This chart is most accurate for observations at 4500 feet above sea level but may be used effectively on all mountains in the Skyfire network.

CLOUD-BREEDING AREAS

A cloud-breeding area may be defined as an area where there is a tendency for cumulus clouds to originate or develop into more advanced stages. To the extent that thunderstorm activity is affected by topography and other surface conditions, one may hope to locate these breeding areas both by theoretical calculation and by cloud observation. Surface effects presumably are more important during the early stages of cumulus development.

Hills help to produce upcurrents for a variety of reasons:

1. Slope Effects:

   a. Mechanical. The orographic effect of wind being forced to blow up the slope helps start the upcurrents, and in addition the mechanically induced upward motion of stable air serves to reduce the air's stability.

   b. Thermal. Since the sun is only rarely overhead, slopes rather than horizontal ground are usually more perpendicular to the sun's rays and thus receive more radiation per unit area. Other considerations being similar, such sloping surfaces would therefore become warmer than horizontal surfaces. In addition, the heat per unit area on slopes is concentrated over a smaller horizontal area; this is important for steep cliffs.

2. Height Effects:

   Air remains in neutral stability if its temperature decreases 5.5° F. per 1000-foot increase of elevation. Although mountaintops are generally cooler than adjacent valleys, they are usually not as much as 5.5° F. cooler per 1000 feet of elevation. Thus they tend to produce thermals more often and of larger size than do adjacent valley areas.

   These effects plus others such as the radiative properties of the vegetation and ground surface and the presence of nearby lakes all vary in importance depending on the meteorological situation. The concept of a breeding area is thus seen to be complicated. In general, however, mountains produce the earliest and also the best thermals.

   The lookout observers collect data on the positions of the first cumulus clouds in their areas. These data have not been analyzed in detail, but they do conform to the above concepts.

   The lookouts have been unanimous in their statements that only rarely do local storms develop out of local small cumulus clouds. Almost invariably the storms move in from another area after they are already well developed. The breeding-area concept is still valid, but the breeding areas may often be far from the regions where the storms produce the damaging lightning.

CLOUD VELOCITY MEASUREMENTS

In addition to providing a convenient tool for calculation of cumulus cloud heights, an abney level calibrated in feet per chain proved to be a useful field instrument for the measurement of upper-cloud velocities (figure 21).

Figure 21. An abney level is a handy tool for calculating cumulus cloud heights and upper-cloud velocities.

The horizontal velocity of cloud elements is almost exactly the air velocity. Even standing wave clouds which have zero velocity contain elements which move with the wind speed; the individual cloud particles cannot be seen from the ground, but a turbulent eddy or cumulus-like puff can almost invariably be seen moving through the larger cloud mass with the speed of the wind.

If the height of the cloud can be estimated, its velocity may be found by measuring its elevation angle and azimuth position at the start and end of a specified time interval. If the cloud motion is directly away from or toward the observer, aximuth remains the same and only elevation need be measured.

During the fire season cloud velocities were estimated with the aid of an abney level, a small, handy, commercially available instrument having more accuracy than needed. The time interval was noted during which a portion of the cloud moved from one elevation angle to another. Elevation angle changes of 80 feet per chain to 60, or 60 to 48, or 48 to 40 all correspond to the same horizontal distances of cloud movement. MF Form D (figure 22) was drawn corresponding to these pre-selected angle changes. It shows velocity in miles per hour for a range of heights and time intervals.

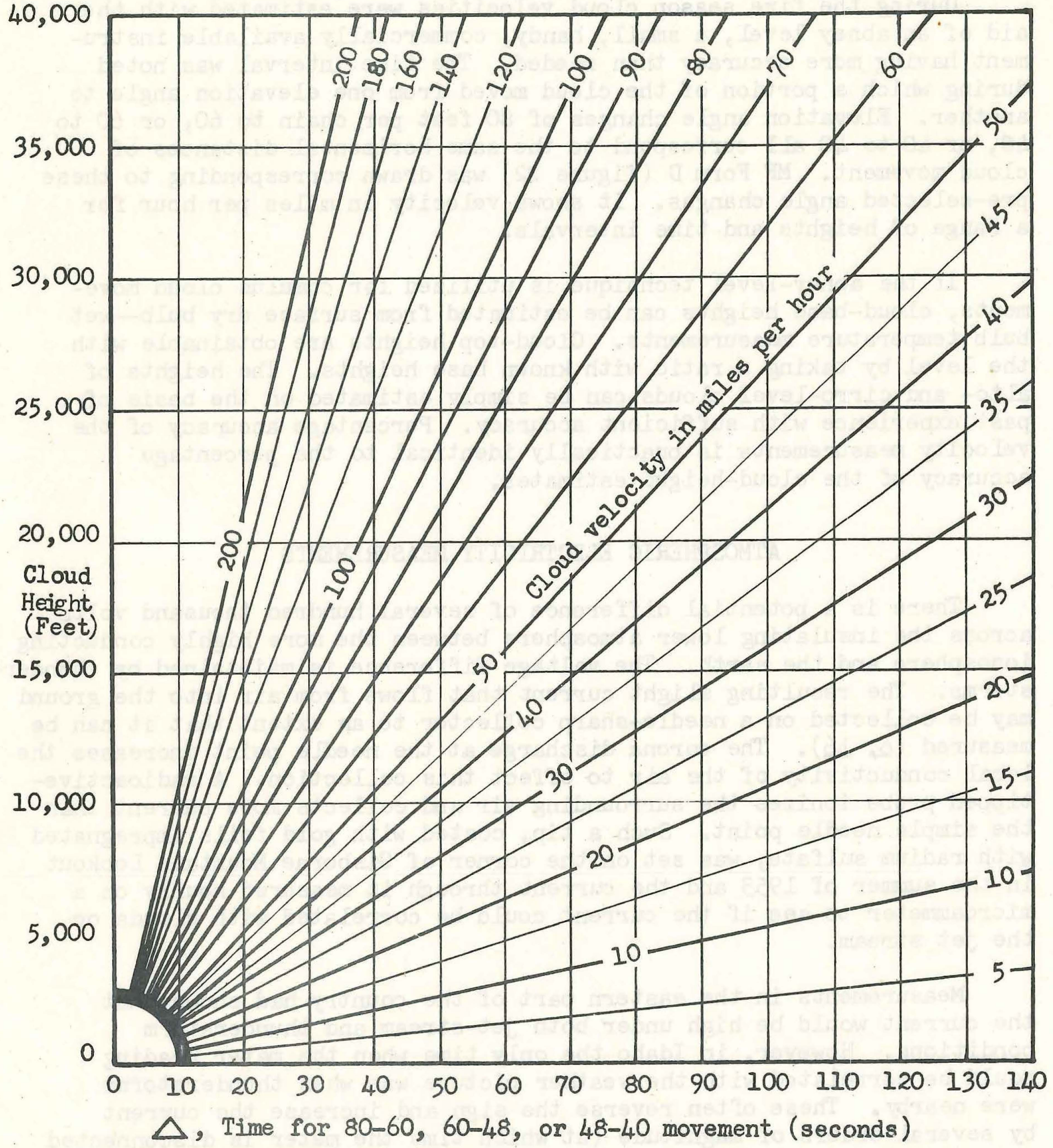
If the abney-level technique is utilized for cumulus cloud movements, cloud-base heights can be estimated from surface dry bulb—wet bulb temperature measurements. Cloud-top heights are obtainable with the level by taking a ratio with known base heights. The heights of alto- and cirro-level clouds can be simply estimated on the basis of past experience with sufficient accuracy. Percentage accuracy of the velocity measurements is practically identical to the percentage accuracy of the cloud-height estimates.

ATMOSPHERIC ELECTRICITY MEASUREMENTS

There is a potential difference of several hundred thousand volts across the insulating lower atmosphere between the more highly conducting ionosphere and the earth. The voltage difference is maintained by thunderstorms. The resulting slight current that flows from air into the ground may be collected on a needle-sharp collector to an extent that it can be measured (6, 16). The corona discharge at the needle point increases the local conductivity of the air to effect this collection. A radioactive-tipped probe ionizes the surrounding air and collects more current than the simple needle point. Such a tip, coated with gold foils impregnated with radium sulfate, was set on the corner of Gisborne Mountain Lookout in the summer of 1953 and the current through it measured hourly on a microammeter to see if the current could be correlated with clouds or the jet stream.

Measurements in the eastern part of the country had shown that the current would be high under both jet-stream and thunderstorm conditions. However, in Idaho the only time when the meter reading could be correlated with the weather picture was when thunderstorms were nearby. These often reverse the sign and increase the current by several orders of magnitude (at which time the meter is disconnected for safety). On other occasions the reading varied between 0.01 and 0.10 microampere, with strong diurnal effect. On a typical day the current will average 0.02 microampere at 0700 P. s. t., reach an average of 0.05 microamp at noon, and drop again to the initial value by 1800. The diurnal variation of the whole earth-to-air gradient structure caused a potential maximum around 1000 P. s. t. (corresponding to maximum thunderstorm activity over the whole world); the variation is only about 15 percent, and cannot account for the needle current readings.

Interpretation of the readings must await further research. Tests are being continued.



Use this chart for finding the velocity of clouds <u>moving directly toward or directly away from the observer</u>. Measure △, the time interval in which the cloud elevation angle changes from 80 feet per chain to 60, or 60 to 48, or 48 to 40 (or the reverse, 40 to 48, 48 to 60, or 60 to 80). At the intersection of △ and the estimated cloud height above the observer, read the cloud velocity. If △ is greater than 140 seconds, use $\frac{1}{2}$ △ and $\frac{1}{2}$ the altitude. For Abney Levels calibrated in degrees, note 80 ft/chain=50.5°, 60 ft/chain=42.3°, 48 ft/chain=36.0°, 40 ft/chain=31.2°.

<u>CLOUD VELOCITY BY ABNEY LEVEL (feet per chain calibration)</u>

Figure 22. Chart used for finding the velocity of clouds with an abney level.

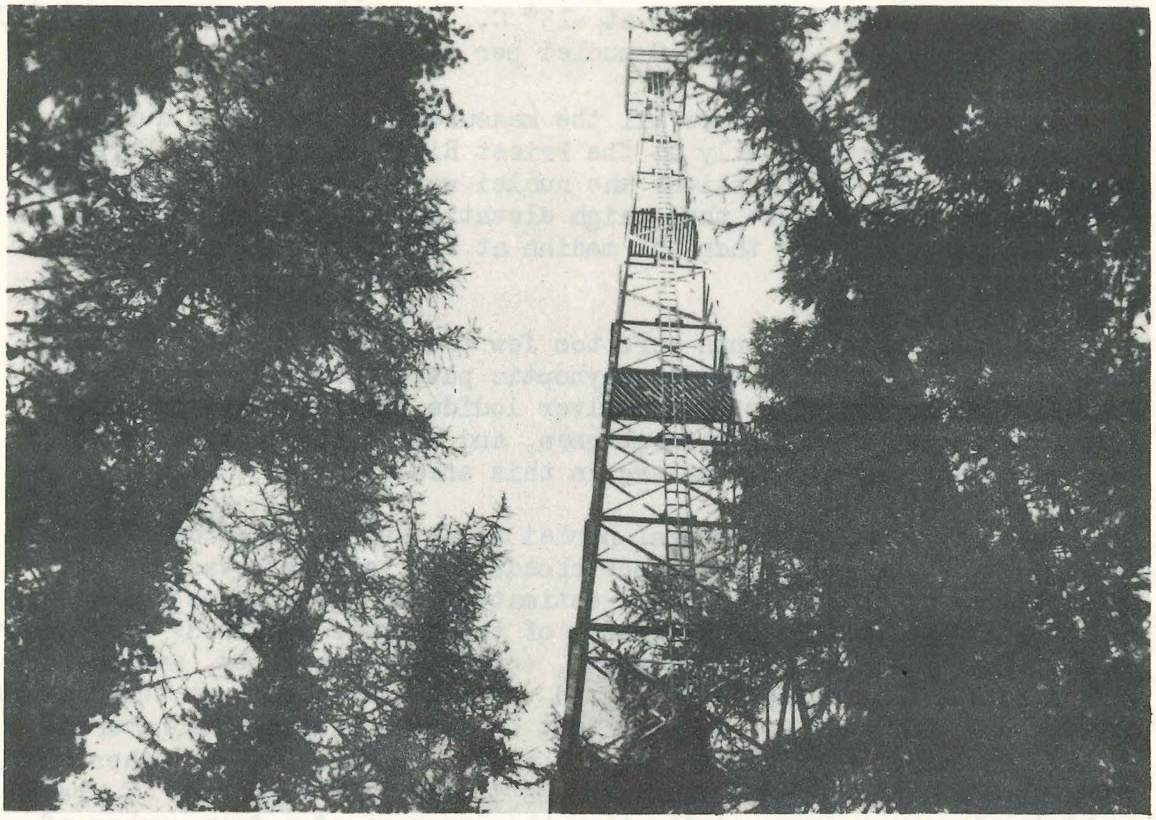


Figure 23. A radioactive-tipped probe for measurement of atmospheric electricity is mounted on the 150-foot meteorological tower at the Priest River Experimental Forest.

NATURAL FREEZING NUCLEI MEASUREMENTS

On 15 days during late August and September of 1953 samples of surface air were checked at several temperatures for the presence of natural freezing nuclei. A portable cold box loaned by Meteorology Research, Inc., was employed for the measurements. In 1947 Schaefer developed the first such portable cold box wherein cold air from dry ice cooled the copper-lined test chamber to the desired temperature. The present unit features a 10-power viewing system and a thermostat-controlled cooling apparatus which is both cooled and powered by the sublimation of dry ice.

The measurement of threshold of freezing nuclei activity varies between -10° C. and -20° C., being most of the time around -13° C.

Counts at -25° C. were from 0.1 to 15 nuclei per cc. of air, with the median being about 2.0 nuclei per cc. On a typical day the counts might be as follows: threshold at -13° C., 0.1 nuclei per cc. at -18° C., 2 nuclei per cc. at -25° C., 10 nuclei per cc. at -38° C.

Except for two instances all the measurements were made during the day in a valley, usually at the Priest River Experimental Forest headquarters. On two occasions the nuclei were counted on North Baldy and Gisborne Lookouts; at these high elevations the nuclei threshold temperatures were lower than the median at low elevations, but not significantly so.

The nuclei measurements were too few to warrant the attempt to correlate them with time of day, synoptic pattern, surface wind, etc. They all do show, however, that silver iodide particles are far more efficient nuclei than the natural ones, and so seeding may be expected to produce results of some nature in this area.

Some information on natural nuclei aloft may be inferred from the appearance of the middle and upper clouds. On various occasions the temperatures of these clouds were estimated from the Spokane radiosonde report and measurements or estimates of the heights of clouds over northern Idaho. There were many cirrus forms, completely glaciated, but there were also numerous examples of liquid cirrocumulus clouds at temperatures between -32° and -40° C., meaning that on many occasions the natural nuclei content at high elevations was extremely low. On the other hand, often altocumulus forms at temperatures in the -10° C. to -20° C. range would develop snow virga, indicating the presence of a fair number of freezing nuclei.

WIDE-ANGLE AND 3-DIMENSIONAL PHOTOGRAPHY

The advantage of wide-angle photographs for almost all cloud photography is obvious. Overlapping photographs, joined together to give a wide-angle panoramic effect, were tried. The inconvenience of this technique initiated the development of some extremely wide-angle-lens cameras, which were first used during the 1954 field season. These inexpensive cameras take an 85-degree picture 2- x 7-inch, on number 120 film (figure 24).

The value of 3-dimensional photography to give both qualitative and quantitative data on cloud forms became apparent. After the 1953 season, stereo pairs were made from consecutive frames from an airborne time-lapse camera. A representative pair of pictures taken from an airplane are shown in figure 25, together with instruction on how they may be viewed without special glasses.

Two sets of stereo cameras have been built for taking photographs of clouds from the ground. One set uses a radio unit to trigger one camera of the pair, the other set effects the synchronization by use of

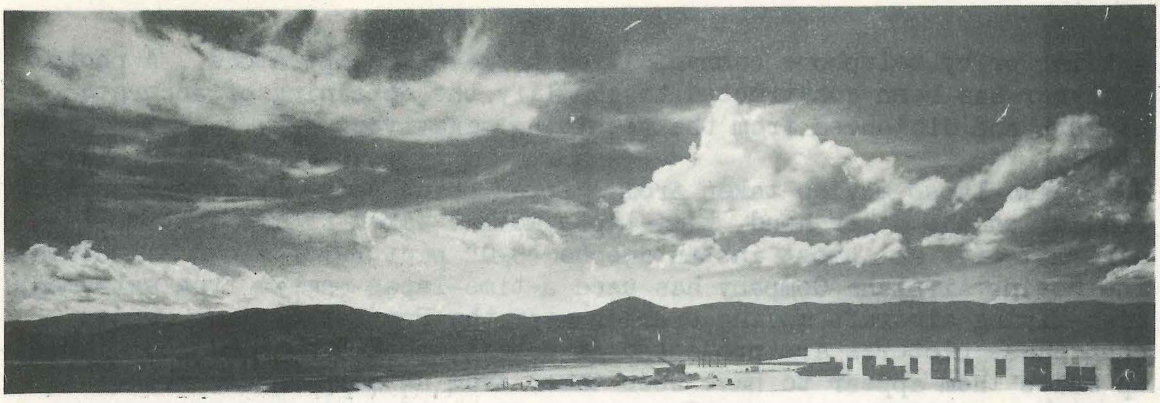


Figure 24. Wide-angle cloud photo of the type taken each day during the 1954 fire season at the U. S. Forest Service Aerial Fire Depot, Missoula, Montana.

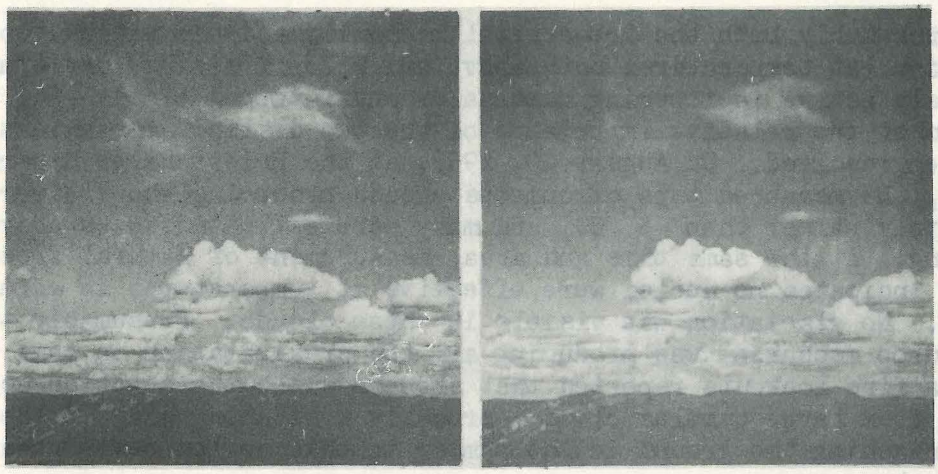


Figure 25. A 3-dimensional photograph pair. These two pictures were taken about a mile apart. If the left one is viewed with the left eye and the right one with the right eye, an exaggerated 3-dimensional effect is produced. Ordinarily such stereo pairs are viewed with a stereo viewer. The viewer is a help, but some people can get the 3-dimensional effect without a viewer. Try this by looking at a distant object, and then moving the pictures in front of your eyes at a distance of a foot or more. Squinting helps greatly.

a timer or by telephone communication between two operators. A photo analyzer has been constructed to simplify the obtaining of accurate heights and distances from the resulting negatives.

Time-lapse movies taken from a fixed point show the development of clouds; on the other hand, time-lapse movies taken from a fast-moving aircraft give an almost instantaneous "3-D" picture of cloud situations. The Boeing Airplane Company has used a time-lapse camera from extremely high-flying aircraft moving over or near the Project Skyfire region. When these pictures are projected at normal speed, the time-scale speed-up makes them appear to have been taken from an airplane or rocket moving about 8000 m. p. h. This apparent rapid motion gives a strong 3-dimensional effect to the pictures, the effect being due to the difference of relative motion between near and distant clouds.

PRECIPITATION MECHANISMS

To date, Project Skyfire has not attempted systematic study of precipitation mechanisms; in fact, special equipment has not been available to help with such a study. However, some ideas can be inferred from visual observations.

Presumably both the ice-crystal mechanism and the water-drop mechanism (at temperatures both above and below freezing) are simultaneously active in towering cumulus or anvil-topped clouds--the vital problem of the relative importance of the two distinct mechanisms has not been resolved. On August 20, 1953, at the Priest River Experimental Forest, the measured tops of cumulus clouds producing showers were definitely warmer than -5° C., and many were estimated to be above freezing. At the same time and area, measurement of natural freezing nuclei indicated no nuclei were effective at temperatures as warm as -11° C. No glaciation was visible in these clouds. Presumably the water-drop mechanism was producing all the precipitation in this case. Various fire lookouts reported that showers without glaciation were common from large cumulus clouds; probably a sizable share of the water reaching the ground in the summer in this region never goes through an ice phase.

It is quite conceivable that the water-drop mechanism may still be a major cause of precipitation in cumulus clouds which have ice anvil tops.

V. METEOROLOGICAL APPROACHES TO REDUCTION OF FIRE DANGER

There are several ways in which weather modification could decrease fire danger. For example, if extra rain can be induced to fall on an area, the chance of a fire starting there will be reduced and the growth of an existing fire will be inhibited. Even an increase of humidity near the ground will tend toward similar effects. The method of fire-danger reduction by increasing precipitation could help with man-caused fires as well as lightning fires. Another approach is to try to decrease the amount of lightning, either by altering the development of thunderstorm clouds, or altering their electrical characteristics. The results of cloud-seeding experiments suggest that one or more of the above approaches will someday reduce the lightning problem. Numerous possible seeding techniques suggest themselves, but much more research needs to be done before any method can be applied in a practical and economical manner. The data being gathered in cloud surveys should provide part of the essential background for future seeding experiments.

REGIONWIDE SEEDING

It may be feasible to seed an entire region for a net precipitation increase, even though the precipitation is uncorrelated with particular fires. Here the danger of floods and the inconvenience which rain causes to commercial interests must be balanced against the possible saving in fire-prevention cost and timber loss. Many projects for regionwide seeding for extra rain have been conducted since 1950. The few published results (4, 5, 8, 9, 11) are in general encouraging but still controversial. Some results seem good, some bad, and so far most are inconclusive. The many unpublished results are similarly encouraging but likewise confusing. Most of the projects stressed ground generators emitting silver iodide smoke. The detailed modes of operation differed considerably.

LOCALIZED SEEDING

Seeding of a specific cloud or local area, which might be employed to help extinguish an existing fire, is better substantiated and is not influenced by the same possible negative economic considerations as is regionwide seeding (12). Dry ice and silver iodide are conventionally employed. In some cases, a forest fire itself helps cause the buildup of a cloud over it from which rain may fall or be induced to fall.

INHIBITING CLOUD BUILDUPS

It is universally agreed that cloud-to-ground lightning strikes require large, convective-type clouds. Therefore any seeding which would prevent such large clouds from forming would inhibit lightning, no matter what final mechanism causes lightning. The most prevalent theories of lightning formation are concerned with some interaction of ice and supercooled water, so it is well to consider what steps could cause modification of electric fields produced by this mechanism. However, the size and energy magnitudes of thunderstorms are so tremendous that control can perhaps only be effected by seeding to prevent large-cloud formations instead of seeding to alter the final form.

The evidence, often contradictory which is available to show how cloud seeding might inhibit the growth of cumulus clouds, is too involved to treat here, but a few points are worth mentioning.

The major source of energy for thunderstorm development comes from the release of latent heat as water vapor condenses into cloud droplets. There is no rule that a certain amount of energy must be utilized by the clouds on a certain afternoon; if one cloud can be inhibited by seeding, it does not "feed" on as much energy as would otherwise be the case. Its lack of growth does not necessarily make more energy available to other clouds--in fact, it may make less energy available to the other clouds. There may thus be a chain effect--inhibiting one cloud may help inhibit later ones. These concepts give one the hope that some sort of seeding can be employed to alter the weather during a whole day over a large area.

When precipitation begins in a cloud, decay sets in rapidly. If dry ice, silver iodide, or sodium chloride seeding were to initiate precipitation earlier than natural conditions, the sizes of clouds could presumably be kept smaller than usual. Since silver iodide or dry ice adds some heat energy to a cloud (by releasing the heat of fusion of water as the supercooled cloud shifts to the ice crystal phase) the cloud may become more stirred up than usual, entrain more dry outside air, cool by evaporation, and decay earlier. Seeding may produce many other effects which negate these actions, but the possibilities do exist of using these mechanisms to inhibit cloud growth.

CHANGING THE ELECTRICAL STRUCTURE OF CLOUDS

It is difficult to decide how to try to alter the characteristics of lightning because as yet there is no one accepted theory as to how lightning originates. Reference (7) includes a comprehensive review of the major lightning mechanisms which have been proposed. Newer reviews will soon be available. The most popular ideas now concern the coexistence of ice and supercooled water. Thus an obvious approach to preventing the buildup of electrical charges is to reduce the amount of supercooled water in a cloud, by overseeding with dry ice or silver iodide. A difficulty with this method is that there are physical limitations to the amount of seeding material which can be put out and effectively distributed within the cloud mass. In addition, if one area is overseeded and a nearby area unseeded, there must be intermediate regions of all other degrees of seeding--and in some of these areas the seeding may produce an unwanted effect.

Some experiments have pointed out the possibility that charge generation may be very dependent on the slight impurities in the water which constitutes a cloud. Tests which simulated cloud conditions implied that the sign of the charge could be changed by changing the type of impurity. Ammonium salts gave a sign opposite to that ordinarily found in the atmosphere. Actual seeding with ammonia did seem to be associated with unusual electrical happenings in the clouds, but the results are merely suggestive of a possible approach to further research.

If a good electrical conductor were placed vertically in a thunderstorm cloud, the charges being generated would presumably discharge through it and neutralize themselves to nondangerous values. Similarly, if the conductor went from earth to the bottom charge center of a cloud, lightning to the ground would be eliminated. A wire would be an effective but impractical conductor for this job. Air ionized by radioactivity could conceivably offer some hope.

The very active and extensive researches of thunderstorms now underway both in the United States and in other countries lead one to believe that much new knowledge in this field will become available within the next few years. It is important that personnel active in Project Skyfire remain in close contact with the advance in knowledge along such lines since it is quite possible that the kind and nature of the field observations being made by Skyfire may be of considerable value in supporting or discounting some of the new ideas advanced in this field of research.

VI. THE JOB AHEAD

The first results of Project Skyfire demonstrate the possibilities of using forest-fire lookout stations for cloud-survey purposes. Continued attention must be given to the development of observational procedures which will permit relatively untrained personnel to obtain useful meteorological information. If it can be demonstrated that this method is practical and useful an extremely important contribution to forest-fire and meteorological field research will be achieved.

If significant progress is to be made in the understanding of dynamic weather processes and lightning fires it is of great importance that both the meteorologist and the forester have adequate field observations available. The development of such procedures is one of the major objectives of Project Skyfire. If successful, it will result in the establishment of a new approach to field research procedures and will tap a tremendous potential for the widespread recording of what may be termed the microstructure of regional cloud systems. By these procedures it should be possible to detect the genesis of storms which become dominant in the development of weather patterns or which lead to serious lightning-fire occurrences. In this manner it may be possible to determine the various forms which natural storms assume and thus establish the patterns which may be expected under different atmospheric conditions. Such results will not be achieved quickly or easily. However it may be expected that this approach, if successful, will be an important step forward in meteorological science and in forestry.

By concentrating the efforts of Project Skyfire toward the understanding of thunderstorm patterns and types in the northwestern mountains, a subject has been selected having great scientific and economic value. If it is feasible to establish the variabilities of natural storms it should be possible to detect effects produced by cloud-seeding procedures. In seeking this goal many other important findings should be made along the way.

By using the Munitalp-University of Washington-Forest Service mobile weather observatory (figure 26) and time-lapse and stereo-photographic recording techniques under various atmospheric conditions a number of new meteorological parameters will be measured and correlated for the first time. Simultaneous measurements of such factors as the concentration of condensation and ice crystal nuclei and atmospheric electricity together with the more standard weather measurements correlated with observed cloud forms and patterns may establish some of the complex interrelationships which combine to produce variations in fire-weather patterns. Much exploratory work is needed in this approach to the chemistry and physics of the atmosphere. The observational procedures which will be established as field experience is gained should be of considerable value in this relatively new phase of meteorology.

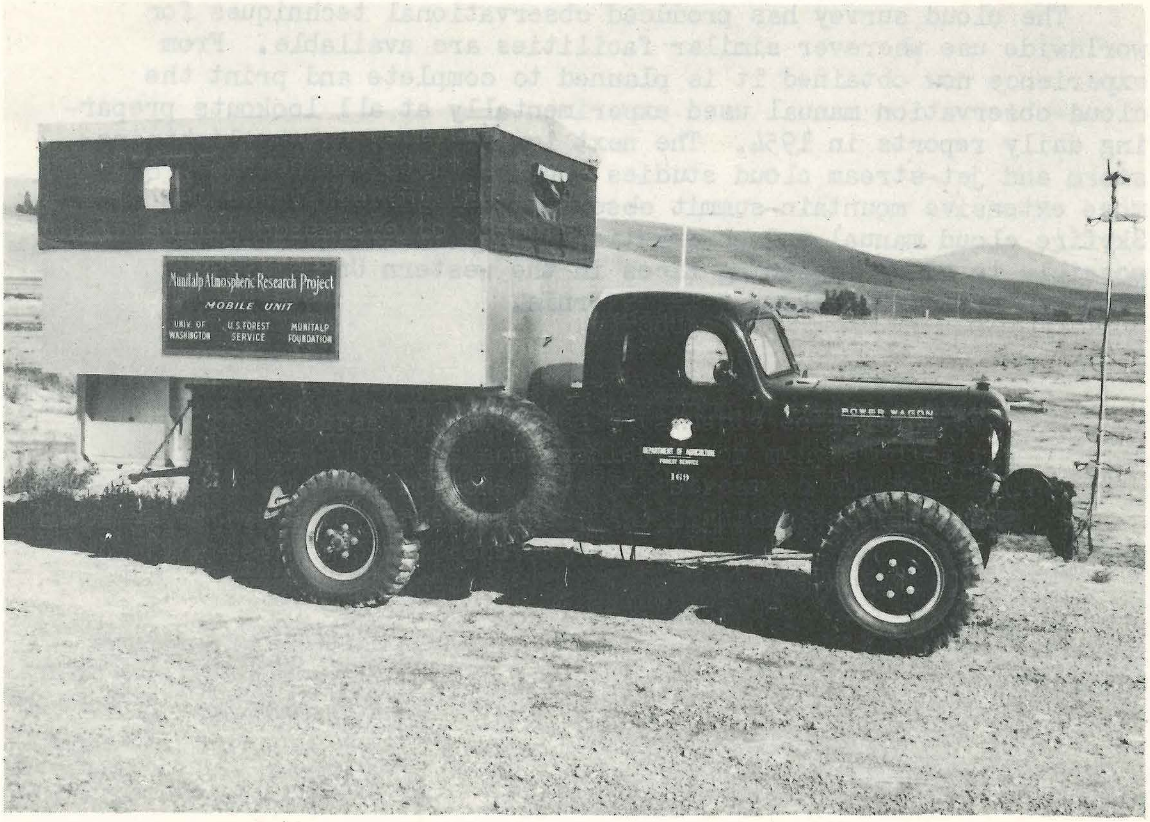


Figure 26. The mobile meteorological laboratory can measure and record many atmospheric factors related to lightning fires.

It is of primary importance that the field results of the Skyfire observational program be reduced to useful information. The cloud survey has already resulted in the accumulation of a considerable mass of data. While a certain quantity of these data are useful, their greatest value to the research program was the field experience which permitted the development of the considerably improved procedures now adopted for use. By having a special research meteorologist active during the 1954 season, by depending on the mountain-summit observers to prepare plotting cards, and by getting daily cloud observations by radio relay, much of the results of the observational program will be analyzed or at least plotted on a day-by-day- schedule. This should greatly reduce the task of analysis after the end of the fire season.

In 1954 the program has produced a valuable collection of meteorological data. This is now available for many studies ranging from analysis of the air motions in a jet stream to the relationship of jet streams to surface winds, and lightning storms and fires to fire-weather conditions.

The cloud survey has produced observational techniques for worldwide use wherever similar facilities are available. From experience now obtained it is planned to complete and print the cloud-observation manual used experimentally at all lookouts preparing daily reports in 1954. The next logical step in the lightning-storm and jet-stream cloud studies would be the establishment of a more extensive mountain-summit observational network, based on the Skyfire cloud manual and observational procedures. It may now be possible to study lightning fires in the western United States from the northern Rockies to California.

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APPENDIX

"The Use of Clouds for Locating the Jet Stream" by Vincent J. Schaefer. Reprinted with the special permission of the Editors and Publishers of "The Aeroplane."

Reprinted from "The Aeroplane," October 30, 1953

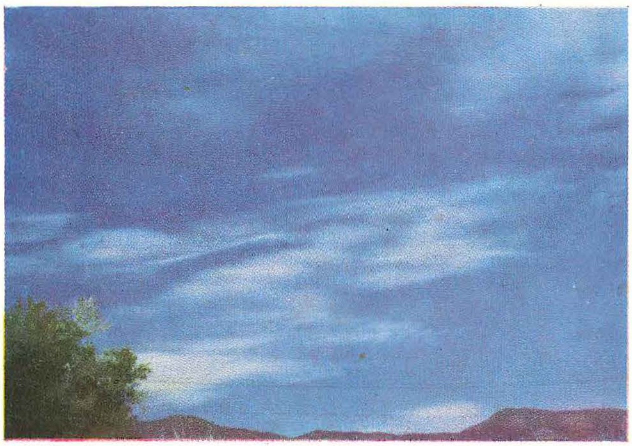
The Use of Clouds for Locating the Jet Stream

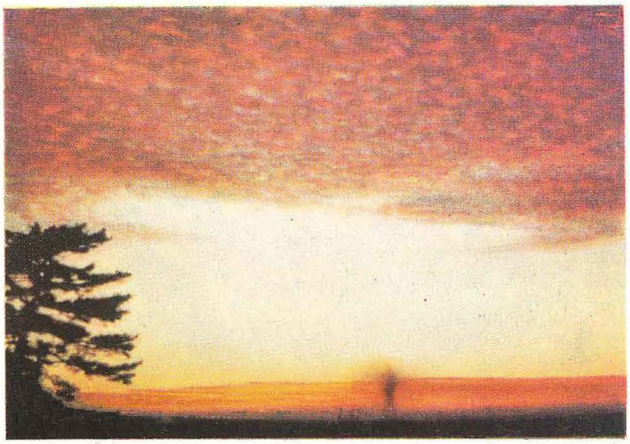
In this article MR. VINCENT J. SCHAEFER, *who is scientific adviser to the Munitalp Foundation Inc., of Connecticut, U.S.A., discusses the possibility of identifying the location and path of the high-velocity winds known as "jet-streams". The article is illustrated by coloured photographs taken by the author.*

As air traffic increases and aeroplanes are built to go faster and higher, knowledge about the properties and characteristics of the atmosphere between 20,000 and 50,000 ft. becomes of increasing importance. Among the interesting features of this portion of the atmosphere are the high-velocity winds which flow in relatively narrow streams through the middle latitudes in an ever-changing and meandering pattern. These are the so-called "jet-streams" and "jet-streaks" which hold great interest to the meteorologist and climatologist as well as the persons who must operate aircraft in such regions of the sky.

These high-velocity air currents which encircle the earth and have a mean west to east movement in both the northern and southern hemispheres are being studied by a rapidly increasing number of scientists. It is not uncommon to have two, and even three, major jets with six or more minor ones passing over North America at one time. Their cross-sectional width ranges from fifty to several hundred miles with velocities from sixty to two hundred or more knots. As might be expected, the higher velocities tend to occur when the streams are narrow in width and thickness. The importance of obtaining a more adequate knowledge of this phenomenon is obvious to those who fly aircraft.

Beginning about 1943, the writer started observing and





Top left, bands of thin lenticular below cirrocumulus patches; flow from horizon toward camera. Top right, cirrus patches and bands at high altitude with flow from left to right. Left, cirrus waves under conditions featured by rapid changes and flow from lower left to upper right. Right, sunrise appearance of thin cirrocumulus with altocumulus near far horizon; flow toward horizon.

photographing spectacular cloud patterns which appeared from time to time in eastern New York. One of the most noticeable features of these cloud forms was their rapid motion through the sky, easily observed despite their high altitude. The direction of cloud motion was seen to vary from north-east through west to south with most cases ranging from north-west to south-west. The clouds often appeared with a leading edge that was quite spectacular, giving evidence of very high velocity and extreme turbulence.

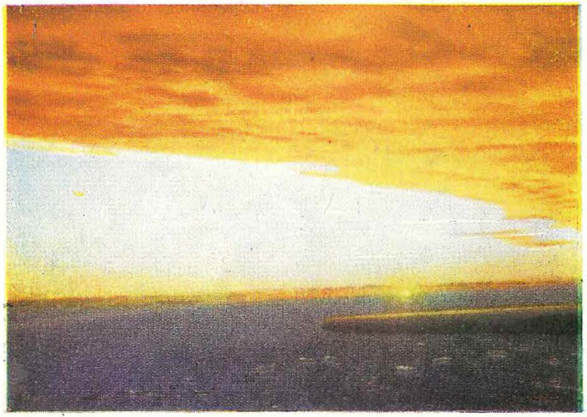
Early in 1952 when 200 and 500 mb charts showing the wind field over the United States became available for study, the writer soon discovered that these unusual cloud patterns were closely related to the major axis of the jet-stream.* These studies showed that the major axis of the jet-stream is closely related to the formation of four easily identified cloud types. Typical examples are shown in the accompanying illustrations. They consist of:—

(i) Lines of cirrus clouds in bands, streamers or sheaves;

(ii) Patches of cirrocumulus and two forms of alto-cumulus;

(iii) The distinctive lenticular forms in either standing or travelling waves; and

(iv) Waves or billows covering localized portions of the sky.



Edge of cirrus shield stretching from New York to Nova Scotia. Flow from lower right toward upper left.

These clouds are as easily recognized from the air as from the ground when the aircraft is underneath the clouds. Whether this will also be true from above is not yet known, although the writer is inclined to believe that they will be as easily recognized from above as from below.

Several hundred observations were made by the writer during the past year, mostly in the United States, but to a limited extent in Great Britain, Scandinavia and Switzerland. As a simple rule for establishing the close proximity of the major axis of the jet-stream the following conditions have now become fairly well established:—

(i) At least three of the four cloud forms should be seen within a period of several hours.

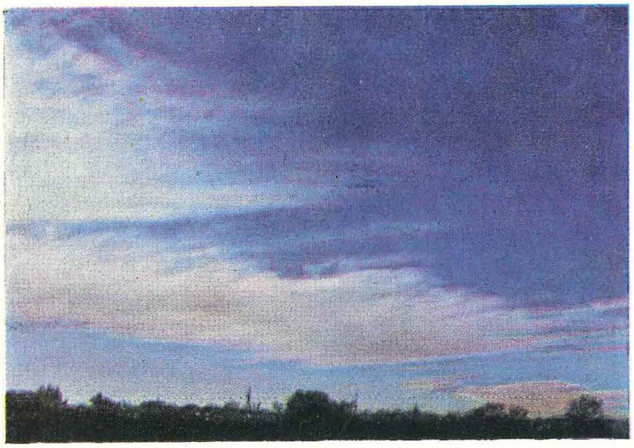
(ii) The clouds must be part of a coherent pattern across the sky.

(iii) They must show evidence of high velocity of movement and rapid changes in structural details.

The rate of motion is easily established from the ground by observing the relative motion of the clouds past some reference point. From a moving aircraft this is more difficult. Under such conditions the rapid changes in structural detail may be used since this is related to the high velocity of movement of the clouds.

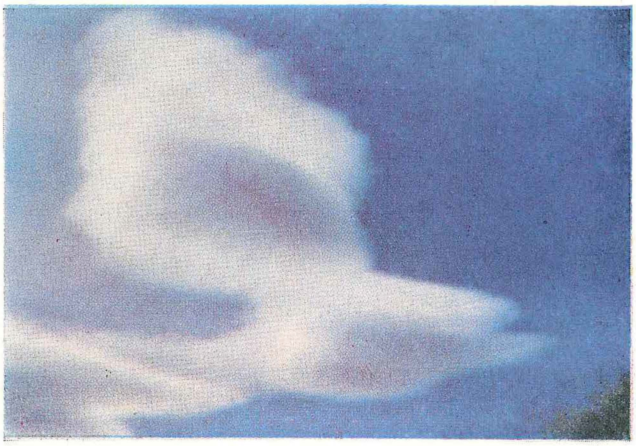
In most cases thus far observed when the major axis of the jet-stream in the 500—300 mb levels was overhead, the sky on the left side major axis looking downwind was cloudless with cool, dry air and unlimited visibility while the sky to the right often exhibited increased cloudiness.

* Schaefer, V. J.—"Clouds of the Jet Stream," *Tellus*, April, 1953—Stockholm.



Left, line of high banded cirrus with flow from upper left to lower right. Right, ripples developing in high cirrus with billows at right-angles to flow in direction from left to right. Above right, very high altocumulus lenticular with trails of ice crystals downwind.

Above left, large and small ripples and high cirrus, with flow from upper left to lower right. Above, high cirrus, forming billows—oriented in various directions with respect to direction of flow, from upper left to lower right; clouds rapidly changing in appearance.



Above, high altocumulus lenticular waves having many layers and shedding ice crystals downwind from right to left.

By observing condensation trails formed in and near jet-stream clouds the writer is of the opinion that certain types of clouds mark regions of extremely smooth air while others will be violently turbulent. Some of them show large-scale shear and circular vortices while others show remarkable standing and travelling waves of great magnitude and velocity.

Nearly 1,000 ft. of time-lapse motion pictures have been obtained during the past year by the writer while engaged with the Munitalp Foundation's Atmospheric Research Project. These show many interesting features, particularly of the relative air motions which are an integral part of the air flow. By studying the relative mass motions of the ice crystals or supercooled water droplets which form the thin clouds mentioned previously, it should be possible to obtain a better understanding of turbulence encountered in regions in and near the jet-stream. Preliminary studies of the time-lapse movies disclose many examples which must represent turbulence. Flights in such clouds synchronized with time-lapse movies should provide valuable data on this important phenomenon.

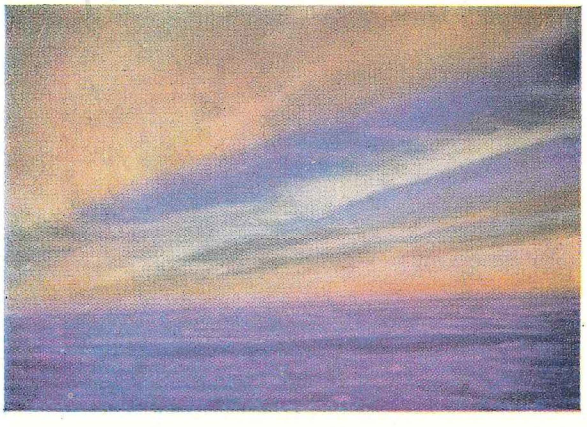
There are a number of problems related to jet-stream clouds which need further attention. These include the following:—

(i) If it is true that specific cloud forms mark the major axis of the jet-stream how feasible is it to use this knowledge in planning a more efficient flight plan ?

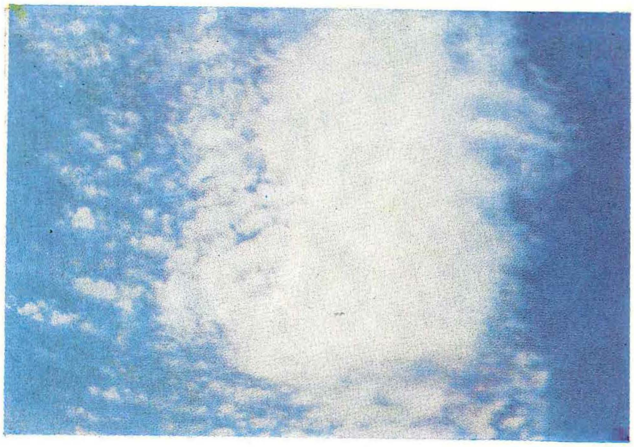
(ii) Do these clouds mark the location of the fastest winds or are they just part of a broad, even flow of air ?

(iii) What types of clouds have bad turbulence and what types are free from turbulence ?

(iv) Is it better to fly in, above or below jet-stream clouds to obtain the most effective use of its high velocity ?



Top, combination of high thin cirrus with veil of lower clouds consisting of altocumulus lenticular and billow forms; flow from lower left horizon to upper right. Lower picture shows high cirrus in lines with long direction indicating jet flow from lower left to upper right.



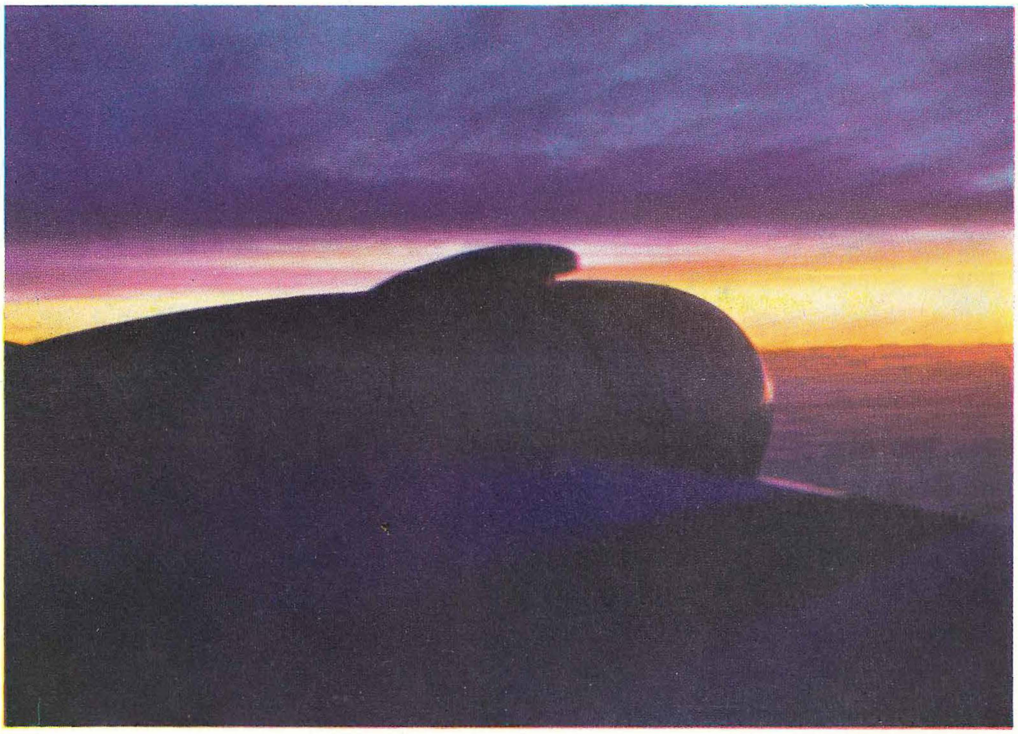
Left, elongated patch of cirrocumulus looking in direction of flow which is toward horizon. Right, series of altocumulus billows. Flow toward horizon.

A number of the problems which require answers may be obtained with a minimum of additional effort. Keen observations aided by simple photography will add much important information to this interesting problem, viz., are jet-stream clouds useful to the aviator while in the air or will they be more useful to the meteorologist in supplementing his scant RAWIN† and PIBAL‡ observational programme from the ground.

With the possible exception of the hurricane or typhoon and the thunderstorm, there are few cloud structures of more interest, greater beauty or more importance than the clouds of the jet-stream.

† RAWIN.—Combination of the words radio and wind. Radio Sonde equipment is sent up on a balloon and this transmits messages, at various heights, of pressure, temperature, humidity and wind.

‡ PIBAL.— Combination of the words pilot and balloon. A plain balloon is sent up and its course is followed with the aid of a theodolite, from which various readings are taken every few minutes.



Time is not far off when the air liners in the higher latitudes will travel with the sun; when that day (or night comes) the sun will not appear to the passengers to rise or set. Meantime it still overtakes the transatlantic air liner as it did the Sabena DC-6 from which this picture of a sunset high over the Atlantic was taken.